A reach, catchment and multiple catchment scale assessment of the patterns and controls of historic upland river planform adjustments

JOYCE, HANNAH,MAY

A reach, catchment and multiple catchment scale assessment of the patterns and controls of historic upland river planform adjustments

Hannah May Joyce

PhD Thesis

A thesis submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy in the Department of Geography, Durham University

March 2020

Declaration of Authorship

I confirm that no part of the material presented in this thesis has previously been submitted by me or any other person for a degree in this or any other university. In all cases, where is relevant, material from the work of others has been acknowledged.

H. M. Joyce

Hannah May Joyce
Department of Geography
Durham University
March 2020

Abstract

The supply, transfer and deposition of sediment from channel headwaters to lowland valleys and lakes, along the upland sediment cascade, is a fundamental process in upland catchment geomorphology. The continuity of the sediment cascade coupled with local geomorphic controls can be partly understood by quantifying river planform adjustments both in space and over time. However, few studies have adopted rigorous quantitative assessments of sediment continuity and planform adjustment beyond the reach scale over historical time periods or considered key controls governing the stability of upland river channels (e.g. climate, anthropogenic activity). This research presents an assessment of the patterns and geomorphic variables of upland river planform adjustment and stability over the past 150 years. A nested sampling strategy is adopted exploring sediment continuity and planform adjustment at the reach, catchment and multiple catchment (regional) scales in the Lake District upland region, north-west England. In total, 270 rivers and streams (total length: 597 km) were studied across 17 catchments in the upland region (total area: 1250 km^2) for six dates from 1860s – 2010. Reach scale investigations focused on exploring the impact of the extreme Storm Desmond (December 2015) flood event on St John's Beck in the Bassenthwaite catchment.

A total of 29,832 stable and adjusting reaches were mapped in the Lake District upland region. Over the full period of analysis (1860s – 2010), 21 % (128 km) of rivers and streams studied were classified as adjusting. Regionally, the highest percentage of river and stream lengths mapped as adjusting between 1860s – 2010 were observed in the Ennerdale (37 %), Wasdale (32 %) and Calder (29 %) catchments (Western Lake District). These catchments showed persistent adjustment and active zones of sedimentation in high order channels over the last 150 years. This is attributed to a high supply of sediment to the fluvial system, greater accommodation space for lateral planform adjustment, and <20 % of the rivers and streams were anthropogenically modified. In contrast, the Kent, Haweswater and Sleddale (Eastern Lake District) showed persistent planform stability and <11 % of the river and stream lengths were mapped as adjusting between 1860s – 2010. This is attributed to narrow topographically confined channels, high specific stream powers and high sediment continuity. In the Kent

catchment >57 % of the river and stream lengths were anthropogenically modified via reinforced banks and flood embankments restricting planform adjustment.

At the reach scale, the influence of a low frequency, high magnitude flood event (Storm Desmond) on river planform adjustment was quantified. However, with increasing spatial and temporal scale the correlation between high magnitude flood events and planform adjustments are harder to define. Anthropogenic activity (e.g. channel engineering, or mining) had a significant influence on river planform adjustment and stability at the reach scale. Regional patterns of geology and the legacy of glacial processes help condition sediment supply, channel slope, and valley bottom width (confinement) thereby setting the general environmental template in which channels adjust in the Lake District. Valley bottom width was found to be an important variable determining the accommodation space for lateral planform adjustment and sedimentation. Planform adjustments occurred in reaches with a mean valley bottom width of 120 ± 190 m.

This research has demonstrated the importance of considering planform stability in a sediment continuity framework across all scales of the stream and river network. The methodology developed provides a quantitative assessment of planform adjustment patterns and geomorphic controls, which aids understanding of historic river behaviour and provides context for current and future river management and restoration strategies.

Acknowledgements

I would like to acknowledge and thank;

Professor Jeff Warburton and Professor Rich Hardy for guiding me along my PhD journey. Their knowledge, support, and enthusiasm has led me to this point, and I am very happy to present this work as my doctoral thesis.

Dr Andy Large for his feedback and guidance during my PhD.

The Lake District National Park Authority, for allowing access and use of the air photographs. I would like to thank Andrew Herbert, Richard Leafe and Claire Redhouse for their support with this research. It has been a great pleasure to carry out research in the Lake District World Heritage Site.

Graham, Sarah and William Chaplin-Bryce for allowing access to St John's Beck and for valuable discussions (accompanied with cake) of the history of the river.

The Department of Geography at Durham University. I have enjoyed every moment studying and being part of the Geography community.

Guy, Victoria and Rebecca for your help in the field and your friendship.

A special thank you to my Mum, Dad and brother Simon for your encouragement and the supply of chocolate to accompany PhD writing!

This PhD research was funded by the Natural Environmental Research Council (NERC) as part of the IAPETUS Doctoral Training Partnership (grant number: NE/L002590/1).

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Rationale

Upland rivers are active geomorphic systems, where steep channel gradients, high runoff and dynamic geomorphic processes result in high rates of sediment production, transfer, deposition and river planform adjustment (Hooke and Redmond, 1989a; Wishart, 2004; Johnson and Warburton, 2002; Warburton, 2010; Joyce et al., 2018). River planform adjustments can create management challenges relating to channel capacity and flood risk, damage to infrastructure and the loss of valuable land, impact habitat diversity and environmental quality (Brookes, 1995; Bravard et al., 1997; Gilvear, 1999; Lane et al., 2007). For example, Figure 1.1 demonstrates the dynamic nature of upland rivers and recent impacts of planform adjustments (bank erosion, sediment aggradation, habitat destruction) in response to the extreme Storm Desmond (December 2015) flood event.

Systematic assessment of the combined spatial and temporal patterns and controls (e.g. climate, anthropogenic activity) of planform adjustments are important for understanding past and present river behaviour; which is required to support future process-form based river restoration and management (Hooke and Redmond, 1989a; Winterbottom, 2000; Brierley and Fryirs, 2005; Grabowski et al., 2014; Lisenby and Fryirs, 2016; Rinaldi et al., 2016; Joyce et al., 2020). However, previous studies have focused on investigating planform adjustments at small spatial scales in response to individual controls (i.e. flood events, mining impacts) (Macklin, 1997). Very few studies (Hooke and Redmond, 1989a; Wishart, 2004; Lisenby and Fryirs, 2016; Joyce et al.,

2020) have adopted rigorous quantitative spatial and temporal assessments of channel planform adjustment and the multiple controlling factors at the catchment or regional scale. The aim of this research is to quantify the spatial patterns and geomorphic variables controlling upland river planform adjustments over the recent era of measurable change (past *c*.150 years) when river channel patterns have been documented in historical records (1860s – present).

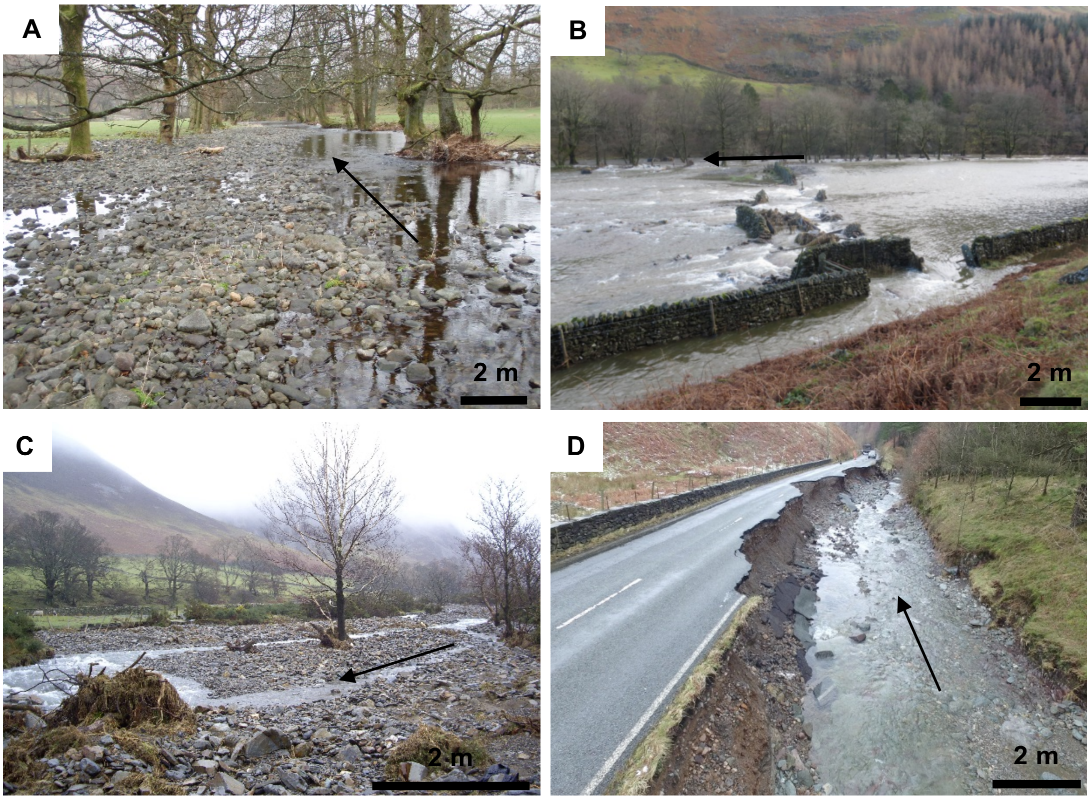


Figure 1.1. Examples of the impacts of channel planform adjustments from the Lake District, UK. Arrows indicate flow direction. A-B: sediment aggradation (A) and reduced channel capacity during flood conditions (B) on St John's Beck (National Grid Reference (NGR) NY 318 203) (source: Graham Chaplin-Bryce, 2015). C) Sediment aggradation and channel widening encroaching on trees and vegetation in Liza Beck near Cockermouth (NGR NY 157 217) 2016. D) River channel bank erosion on Raise Beck undercutting the A591 road from Kendal to Keswick, after Storm Desmond, 2015 (source: Atlantic Geomatics, 2015).

1.2 River adjustments and sediment continuity

River channels typically adjust in response to changes in the balance between the supply, transfer and deposition of sediment relative to the discharge regime (Leopold and Maddock; 1953; Lewin, 1977; Richards, 1982; Thorne, 1997; Constantine et al., 2014). River planform adjustments can therefore indicate patterns of sediment continuity, defined as the supply, transfer, deposition or exchange of sediment from catchment headwaters to valley sink over time (Joyce et al., 2018). Sediment continuity is distinct from the concept of sediment connectivity (Hooke, 2003; Bracken et al., 2015) as it describes the pathways for sediment transfer by quantifying the movement and storage of sediment mass via changes in channel planform (Joyce et al., 2018; 2020).

River adjustments can be quantified in three-dimensions (3D) through changes in the channel cross sectional area, or via two-dimensional (2D) planform adjustments (Ashmore and Church, 1998; Simon et al., 2016). Three-dimensional assessments of river adjustments provide a detailed perspective of channel morphology but can be limited to small spatial scales over short time periods, and therefore they do not provide a historical perspective of source to sink understanding of sediment continuity (Raven et al., 2009; Raven et al., 2010). Instead, the analysis of 2D planform adjustments by comparing historic maps and remote sensed air photographs provides the opportunity to quantify sediment continuity over longer time periods and at larger spatial scales (Hooke and Redmond, 1989b; Winterbottom, 2000; Piégay et al., 2020). For example, in laterally unconfined settings a high sediment supply relative to the discharge (transport-limited conditions) can lead to sediment aggradation and the development of channel bars which can be identified in historic maps and air photographs (Schumm, 1977). Sediment aggradation can subsequently reduce channel capacity and redirect the flow, enhancing bank erosion, promoting channel width and bar size to increase. In contrast, if sediment supply decreases relative to the flow (supply-limited conditions) bars become less extensive, the channel displays a uniform 2D planform, where erosion of the bed and banks is the prominent channel defining mechanism (Schumm, 1977). Two-dimensionally stable channel reaches (i.e. showing zero adjustment) indicate a balance in the supply, transfer and deposition of sediment relative to the discharge regime over time. Understanding 2D planform adjustment and stability is therefore a useful diagnostic for understanding process-form relationships and catchment scale sediment continuity over time. However, few studies adopt this approach and quantify sediment continuity at the catchment scale, particularly in upland regions.

1.3 Dynamic upland catchments

Upland rivers generate some of the highest annual global sediment yields (Milliman and Syvitski, 1992). In the UK, upland regions are commonly defined as areas of substantial land above 300 m elevation with intervening valley floors at lower elevations (Lewin, 1981; Newson, 1981; Allaby; 1983; Atherden, 1992; Averis et al., 2004). Using this definition 20 - 30 % of the UK is defined as upland (Lewin, 1981; Atherden, 1992). Upland headwater catchments, dominated by low order streams, are particularly susceptible to planform adjustments, due to the steep channel gradients, high annual rainfall totals and flashy discharge regimes (Hooke and Redmond, 1989a). These characteristics result in high rates of sediment production, transfer and deposition and subsequent geomorphic change through the upland sediment cascade process domains (Schumm, 1977; Johnson and Warburton, 2002; Wishart, 2004; Burt and Alison, 2010; Warburton, 2010; Joyce et al., 2018). Hooke and Redmond (1989a) estimated that over an 89 year period (1870-1959) 35 % of UK upland rivers have experienced some degree of planform adjustment from minor bend adjustments to large scale planform avulsions.

Upland river planform adjustments create ongoing management challenges, (Fig. 1.1). These challenges were recently demonstrated during the extreme Storm Desmond rainfall event (Cumbria, December 2015), (Fig. 1.1), which caused severe fluvial flooding, river bank erosion, deposition of coarse sediment across agricultural and urban land and disruption to infrastructure (Joyce et al., 2018). Sedimentation and erosion concerns are likely to be amplified in the future due to predicted increases in discharge due to climate change which will affect the intensity and frequency of flood events and future potential for sediment transfer and planform adjustment (Coulthard and Macklin, 2001; Watts et al., 2015). Upland regions are therefore dynamic systems and provide a relevant focus of this thesis to develop and apply a methodology to assess the patterns and controls of channel planform adjustment over time.

1.4 Exogenic and endogenic controls on planform adjustment and stability

Contemporary river planform reflects the legacy of past and present interacting exogenic and endogenic factors controlling water and sediment continuity across a catchment, these variables and linkages to channel planform are summarised in Figure 1.2 (Schumm, 1977; Ferguson, 1987; Gardiner, 1990; Newson, 1997; Brewer and Lewin, 1998; Sear et al., 2003; Bizzi et al., 2019).

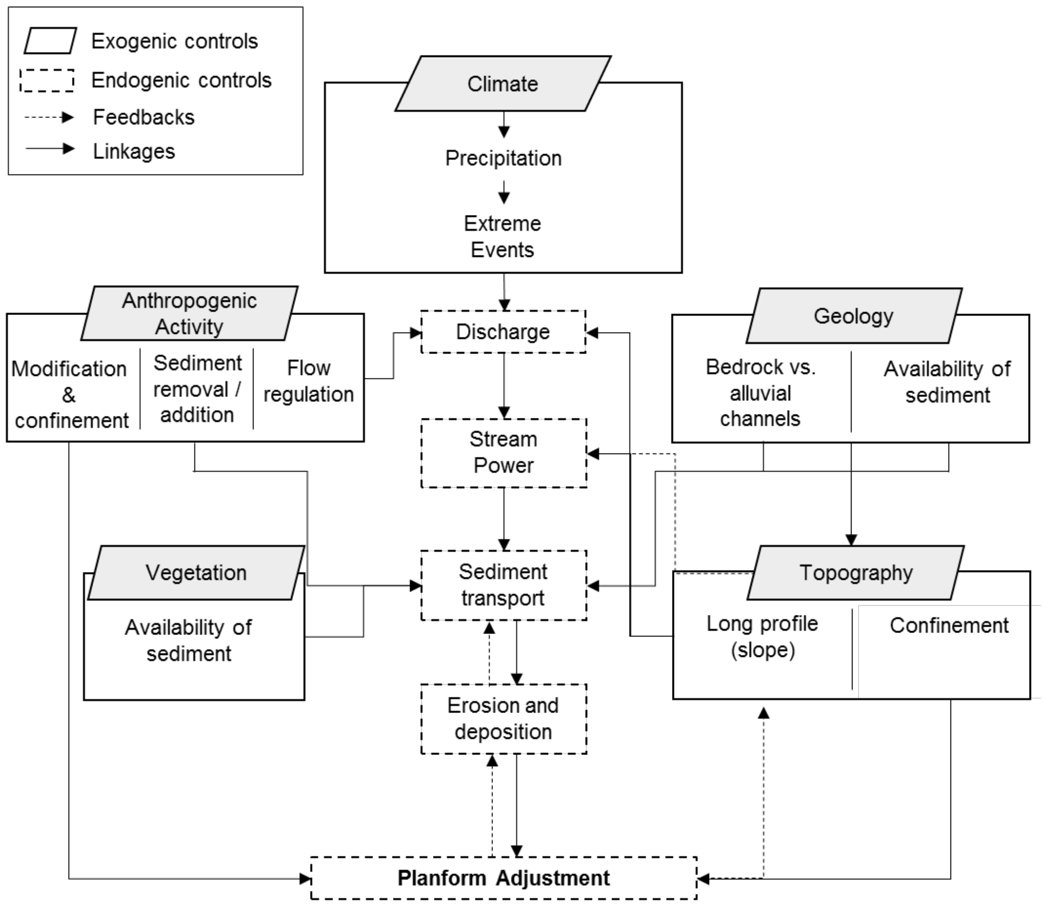


Figure 1.2. Conceptual diagram of exogenic and endogenic variable interactions that influence the balance of water and sediment continuity through a reach, and therefore channel planform. Modified from Ashworth and Ferguson (1989); Sear et al., (2003).

In Figure 1.2, climate influences the frequency and magnitude of flood events and therefore stream power and energy available for sediment erosion, transfer and deposition (Wolman and Miller, 1960; Newson, 1980a; Milne, 1982; McEwen, 1994; Rumsby and Macklin, 1994; Werritty and Leys, 2001; Johnson and Warburton, 2002; Surian et al., 2016). Geological and glacial processes that occurred over the last millennium in UK upland catchments (Schumm and Lichty, 1965; Brewer and Lewin, 1998; Higgitt et al., 2001) determined the presence of over deepened basins, lakes, availability of sediment, sediment type, topographic confinement and channel slope (Milne, 1983a; Fryirs et al., 2016). Vegetation influences river bank stability (Hey and Thorne, 1986; Millar, 2000; Gurnell, 2014). Anthropogenic activity impacts channel planform through channelization (Brookes et al., 1983; Brookes, 1987, 1988; Gilvear and Winterbottom, 1992; Parsons and Gilvear, 2002; Surian and Rinaldi, 2003), restoration (Sear, 1994; RRC, 2013); alterations to the sediment regime (Macklin, 1997; Rinaldi et al., 2005; Heckmann et al., 2017) flow regulation and dams (Petts, 1979; Williams and Wolman, 1984; Kondolf, 1997; Pique et al., 2017). Therefore, channels adjust in response to these collective controls. In Figure 1.2, exogenic controls directly and indirectly influence the endogenic controls (discharge, stream power, sediment supply, transport, erosion and deposition), which constitute the central spine determining sediment continuity and channel planform (Fig. 1.2). At present, there is no consistent methodology to quantify the collective variables controlling channel planform adjustment or stability spatially and temporally in upland regions.

1.5 Temporal patterns of planform adjustment and stability

Two-dimensional channel planform adjustment and stability can be readily identified from available historic maps and air photographs over the last 150 years, defined herein as a period of 'measurable change' (Schumm and Lichty, 1965; Hooke and Redmond, 1989b; Winterbottom, 2000; Higgitt et al., 2001; Grabowski and Gurnell, 2016). Over the last 150 years, there have been changes in climate, anthropogenic activity and river management across upland regions which can influence water and sediment continuity and therefore the rates and patterns of planform adjustment (Fig. 1.3) (Winterbottom, 2000; Higgitt et al., 2001; Rumsby, 2001; Brown et al., 2017). For example, a warming climate has been associated with increases in high intensity convective rainfall events, causing an increase in fluvial flooding, sediment transfer and planform change within upland rivers (Fig. 1.3), (Higgitt et al., 2001; Foulds and Macklin, 2016). There has been a 'great acceleration' (Brown et al., 2017) of anthropogenic activity, including changes in land use and direct channel modification over the last 150 years in the era of the Anthropocene (Fig. 1.3). Factors that influence the temporal pattern of planform adjustments can occur both at the reach and catchment scales initiating immediate (e.g. floods), progressive (e.g. climate or land use change) or discontinuous (e.g. sediment mining) or permanent disturbance (e.g. dam, bank protection) on channel planform (Dufour and Piégay, 2009; Piégay et al., 2020). Therefore, understanding the collective controls of historical patterns of change is important for identifying and understanding historic, present and potential future zones of persistent stability or adjustment (Hooke and Redmond, 1989a, 1989b).

In the UK, 2D channel planform adjustment and stability can be readily identified by comparing available historic maps (Ordnance Survey County Series and National Grid map editions) and air photographs over the past 150 years (Harley, 1965a, 1965b; Werritty and Ferguson, 1980; Downward et al., 1994; Winterbottom, 2000; Gilvear and Bryant, 2016; Joyce et al., 2020). 1D and 2D information on endogenic and exogenic controls (Fig. 1.2) such as channel slope, width, catchment area, stream power and land use can also be easily quantified using digital terrain models (DTM), geology data, discharge and land management records (Marcus and Fonstad, 2010; Bizzi et al., 2019). Despite the range of available data, there is lack of a consistent quantitative methodology that takes a catchment wide assessment of planform adjustments from channel headwaters to valley sink and the key variables influencing planform adjustments over the last 150 years (Bizzi et al., 2019; Joyce et al., 2020).

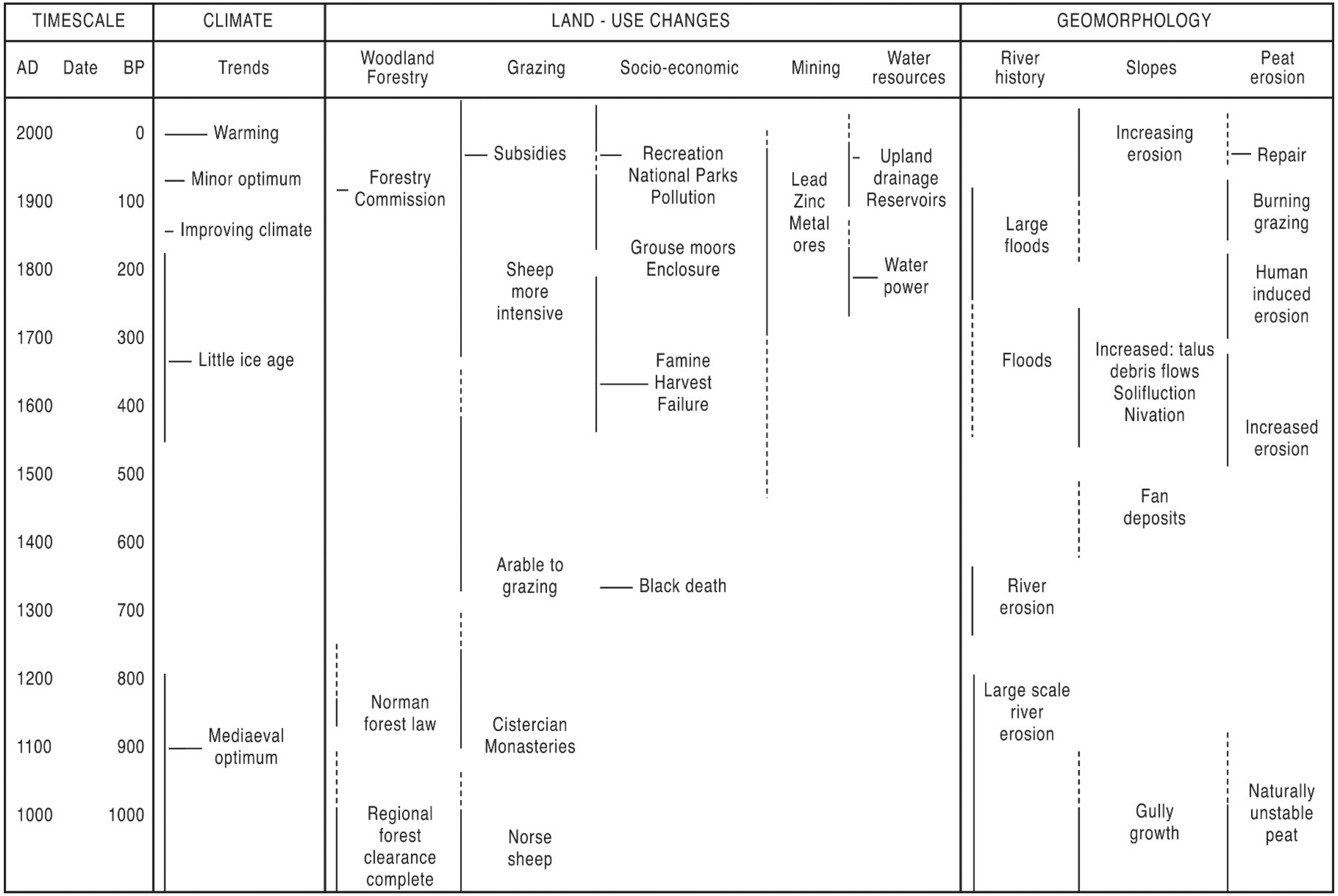


Figure 1.3. Changes in upland region over past millennium, with increased changes in climate, land use and geomorphology over the last century (source: Higgitt et al., 2001).

1.6 Reach and catchment scale analysis of planform adjustment and stability

Frequently, channel planform adjustments have been investigated at the reach scale, a short length of the river (e.g. 500 m), or on a single river, at locations of adjustment, or on high stream order channels (Schumm, 1969; Lewin and Hughes, 1976; Lewin, 1977; Lewin et al., 1977; Blacknell, 1981; Milne, 1982; Milne, 1983a, 1983b; Warburton et al., 2002; Wishart et al., 2008; Hooke and Yorke, 2010). Although very useful at the local scale, these studies often fail to characterise the spatial and temporal patterns of sediment continuity because:

i) active adjustment reaches are not evaluated in the broader catchment context, for example, along the entire length of a river or between rivers in the same catchment where similar geographic conditions occur (Fryirs et al., 2009; Gurnell et al., 2016);

ii) the historic pattern of channel adjustment and stability is not assessed; and,

iii) the geomorphic variables of both stable and active channel reaches are not quantified, which is needed to explain and identify the locations susceptible to adjustment.

Despite these limitations, 3D reach scale assessments allow detailed understanding of river behaviour and sediment dynamics (i.e. sediment size and mass, transport rate), (Hooke and Redmond, 1989a; Joyce et al., 2018). Therefore, it is necessary to place detailed reach scale planform adjustment studies in the catchment and regional context (Macklin et al., 1998; Piégay et al., 2016). Linking reach scale studies to wider catchment assessments of river channel planform adjustment will enable a better understanding of the types of planform adjustment and whether adjustments are typical or anomalous in the spatial and temporal context.

Catchment scale assessments of river channel planform adjustments can be used to understand sediment continuity through the production, transfer and deposition process domains of the upland sediment cascade (Schumm, 1977; Montgomery, 1999; Joyce et al., 2018, 2020). The benefit of catchment scale planform adjustment studies are widely recognised (Hooke and Redmond, 1989a; Rosgen, 1994; Macklin et al., 1998; Wishart, 2004; Lisenby and Fryirs, 2016; England and Gurnell, 2016; Joyce et al., 2020), and reinforced in recent European and UK legislation, which emphasise the need for integrated and catchment wide consistent assessment of the hydro-morphological condition of rivers (i.e. understanding of inter-relationship between endogenic and exogenic controls and channel planform adjustment) (*c.f.* European Water Framework Directive (European Commission, 2000); Floods Directive (European Commission, 2007), UK governmental 25 year Environmental Plan), (Rinaldi et al., 2015a).

Fluvial audits and hierarchal river and catchment characterisation approaches (Sear et al., 1995; Environment Agency, 2005; Brierley and Fryirs, 2005; Rinaldi et al., 2015a; Gurnell et al., 2016), which couple geomorphological field assessments and the use of historical sources of information and remote sensed data of river planform (Sear et al., 1995; Environment Agency, 2005; Martínez-Fernández et al., 2019) have provided an important step towards understanding the geomorphic processes and styles of river planform adjustments at the reach and catchment scale (Brierley and Fryirs, 2005; Gurnell et al., 2016). However, these approaches are often qualitative (Benda et al., 2004), use complex scoring indexes to characterise river types (Rinaldi et al., 2013; Rinaldi et al., 2015a; Rinaldi et al., 2015b), do not directly quantify the temporal trajectory of planform adjustment and fail to capture the geomorphic characteristics of planform adjustment within the overall catchment structure (Lisenby and Fryirs, 2016).

Understanding the spatial pattern and geomorphic characteristics of planform adjustment across multiple catchments in a region represents an important area for further research development (Macklin et al., 1998; Brewer et al., 2000; Piégay et al., 2020). Currently there is no consistent methodology to develop a quantitative regional database of channel planform adjustments and the geomorphic variables from headwater channels to sink (Downs, 1994, 1995). Regional assessments of river planform adjustments can be used to identify if adjustment patterns and controls are catchment specific, or similar across a geographically similar region and, identify 'active' and 'stable' catchments. This can enable a wider understanding of sediment continuity and process-form behaviour to aid with the predictions of where adjustments might occur in the future and identify locations for management or restoration priorities at a regional level (Macklin et al., 1998; Grabowski and Gurnell, 2014; Wohl et al., 2015; Brierley and Fryirs, 2016; Lisenby and Fryirs, 2016; Hooke et al., 2019). However, few studies take a rigorous quantitative assessment of planform adjustments from channel headwaters to sink at the catchment or multiple catchment (regional) scale (Lisenby and Fryirs, 2016; Joyce et al., 2020), or make comparisons between planform adjustment patterns between multiple catchments in a region over the last 150 years. (Wishart, 2004).

1.7 Thesis aim and research questions

The aim of this research is to quantify the spatial patterns and geomorphic variables of upland river planform adjustment and stability over the past 150 years, at the reach, catchment and multiple catchment (regional) scale. This will allow spatial and temporal patterns of planform adjustment to be identified, which is required to support process-based river management and restoration. A series of research questions (RQ) have been designed to achieve this aim:

RQ1. How do river planform adjustments vary spatially across multiple catchments in a region over the last 150 years?

RQ2. What are the dominant exogenic and endogenic variables influencing the spatial distribution of river planform adjustments, and is this pattern catchment specific, or similar across multiple catchments in a region?

RQ3. What is the influence of low frequency, high magnitude flood events on river planform at the reach, catchment and multiple catchment scale over the last 150 years?

1.8 Thesis structure and chapter objectives

The thesis comprises of six chapters following the Introduction. Chapter 2 reviews the current understanding of sediment dynamics and planform adjustments in upland regions, focusing on UK uplands. Chapter 3 describes the Lake District upland region, a relevant upland region study site to investigate the patterns and controls of planform adjustment. The results chapters (Chapter 4, 5, 6) explore the patterns and controls of planform adjustments at the three spatial scales constituting the reach, catchment and multiple catchment (regional) scale. Chapters 4, 5 and 6 are based on research papers that have been either published or are in preparation for peer-reviewed journals. Therefore, these chapters are presented in a self-contained style with introduction, aims and objectives, description of study site and methods, and presentation and discussion of the results. Chapter 7 concludes the main findings of this research linking the reach, catchment and regional scale spatial scales and recommends directions for future research. The Chapter objectives are described below.

1.8.1 Chapter 2

The objective of Chapter 2 is to review existing literature relating to the patterns and controls of river adjustment and the methodologies used to assess planform adjustment and stability in UK upland regions. The upland sediment cascade is presented as a framework to understand spatial patterns of planform adjustment and stability in the upland region. The review highlights that previous planform adjustment studies have been focused at the reach scale and that there is a need for combined catchment scale assessments, from upland headwater catchments to lowland valley and lake sinks. The Chapter discusses the importance of assessing planform adjustments over the last 150 years. The literature review justifies the selection of an upland region for the study site (Chapter 3) and provides context for the methodology developed and used in Chapters 4, 5 and 6.

1.8.2 Chapter 3

The objective of Chapter 3 is to identify and describe a study region where channel planform adjustments are frequent, can be quantified from channel headwaters to sink, and there is available historic and topographic data. The Lake District upland region, north-west England, is a suitable upland study site because it has: dynamic upland rivers and suitable spatial and temporal data available for the last 150 years. The Chapter provides an overview of the Lake District study region, which comprises of 17 catchments. The geology, drainage pattern, climate and available data in the Lake District region are presented. The history of river management and its potential influence on planform in the region is also discussed. The Chapter locates the three different spatial scales addressed in the thesis, which include: the reach (Chapter 4), catchment (Chapter 5), and multiple catchment (regional) scale (Chapter 6).

1.8.3 Chapter 4

The objective of Chapter 4 is to quantify the influence of a low frequency, high magnitude flood event (Storm Desmond, December 2015) on channel planform and sediment continuity at the reach scale. The chapter discusses a sediment budget approach that was used to quantify the transfer and deposition of sediment along St John's Beck, an upland river in the Lake District, in response to the extreme Storm Desmond flood. Field measurements show 6500 ± 710 t of sediment was eroded or scoured from the river floodplains, banks and bed during the event, with 6300 ± 570 t of sediment deposited in the channel or on the surrounding floodplains. The results highlight the importance of valley floodplains in disrupting longitudinal sediment continuity by storing large quantities of sediment during extreme events causing sediment attenuation downstream. This work has been published in Geomorphology and a copy of the paper is included in Appendix A:

Joyce, H.M., Hardy, R.J., Warburton, J. and Large, A.R., (2018). Sediment continuity through the upland sediment cascade: geomorphic response of an upland river to an extreme flood event. Geomorphology, 317, pp. 45-61.

1.8.4 Chapter 5

The objective of Chapter 5 is to develop a methodology to assess the patterns and controls of planform adjustment and stability over the period of measurable change at the catchment scale. The methodology developed is applied and tested on 18 rivers (total length = 24 km) in the upland headwaters of the previously glaciated Wasdale catchment (45 km^2), in the Lake District study region. Planform adjustments were mapped from historic maps and air photographs over six time windows covering the last 150 years. A total of 1048 adjustment and stable reaches were mapped. Over the full period of analysis (1860s – 2010) 32 % (8 km) of the channels studied were adjusting. Contrasts were identified between the geomorphic characteristics (slope, catchment area, unit specific stream power, channel width and valley bottom width) of adjusting and stable reaches. The methodology developed provides a quantitative assessment of planform adjustment patterns and geomorphic controls, which is applied at the regional scale in Chapter 6. This work has been published in Geomorphology and a copy of the paper is included in Appendix B:

Joyce, H.M., Warburton, J., Hardy, R.J., (2020). A catchment scale assessment of patterns and controls of historic 2D river planform adjustment. Geomorphology https://doi.org/10.1016/j.geomorph.2020.107046

1.8.5 Chapter 6

The objective of Chapter 6 is to take a multiple catchment scale assessment of the patterns and controls of historic 2D river planform adjustments. The Chapter presents the first multiple catchment scale assessment of patterns and controls of 2D planform adjustment and stability in the Lake District upland region. The methodology developed and tested in Chapter 5 is applied to the remaining 16 catchments in the Lake District study region. The results show, low order headwater channels were topographically confined, with steep channel slopes, high specific stream powers and narrow channel widths and therefore these channels exhibited relative 2D stability. In contrast, the floodplain valley transfer zone is characterised as an area of sediment discontinuity with local sedimentation zones as the channel slope and stream power decreases and valley bottom width increases creating accommodation space for sediment deposition and lateral adjustment. Regionally, over the full period of analysis (1860s – 2010) 21 % (128 km) of channel lengths were mapped as adjusting. The temporal analysis highlighted catchments showing persistent adjustment (Ennerdale, Wasdale and Calder) and stability (Sleddale, Kent and Haweswater) across the upland region. Stable and adjusting reaches had statistically significant differences between the mean geomorphic characteristics: valley bottom width, channel width, slope and specific stream power.

1.8.6 Chapter 7

Chapter 7 summaries the major findings of this research in relation to the research questions outlined in Chapter 1. Regionally, relative 2D planform stability was observed in confined second order headwater channels. In contrast, a higher frequency of planform adjustments were observed where channels became locally unconfined and stream order number increased across the Lake District upland region. Valley bottom width was therefore found to be an important exogenic variable influencing accommodation space for planform adjustment. However, patterns of planform adjustment showed local catchment and reach scale variability where anthropogenic activities were present. At the reach scale, extreme flood events were shown to have a significant influence on sediment continuity and planform adjustment. However, at the regional scale the link between planform adjustment and flood frequency and magnitude was harder to define. This is attributed to the availability of data, the multiple interacting endogenic and exogenic variables influencing planform adjustment and stability, and the complex response of planform to such controls. Chapter 7 concludes by commenting on the implications of the results for future management of upland catchments.

Chapter 2

Sediment dynamics and planform adjustment controls in upland catchments

2.1 Chapter summary

The aim of this research is to quantify the spatial and temporal patterns and controls of upland river planform adjustment and stability, and therefore there is a need to review the current understanding of the topic. This Chapter provides an overview of the existing literature relating to sediment supply, transfer and deposition, planform adjustment controls and the methodologies used to assess planform adjustment and stability, focusing on UK examples. The Chapter concludes that previous planform adjustment studies have been focused at the reach scale, on individual exogenic controls. Therefore, there is a need for combined reach, catchment and multiple catchment scale assessments to capture historic patterns of planform adjustment and the collective controls influencing sediment continuity.

2.2 The Upland Sediment Cascade

The upland sediment cascade (USC) describes the supply, transfer and storage of catchment sediment from source to sink (Rapp, 1960; Chorley and Kennedy, 1971; Dietrich and Dunne, 1978; Slaymaker, 1991; Burt and Allison, 2010). The USC provides a structure to understand the spatial patterns of sediment continuity, channel planform adjustment and stability in upland catchments. Figure 2.1 provides a framework for the USC displaying the main sediment sources, sinks and sediment continuity over time that are often characterised in upland sediment budget studies (Rapp, 1960; Dietrich and Dunne, 1978; Reid and Dunne, 1996; Fuller et al*.*, 2002;

Brewer and Passmore, 2002). In this thesis, the USC is adapted from Schumm's (1977) simple sediment transfer model that divides the fluvial system into the production, transfer and deposition zones. In many upland regions, the presence of glacially formed over deepened basins, which form waterbodies, restrict sediment continuity between the zones (Herdendorf, 1982; Foster, 2010; McDougall and Evans, 2015). These basins occur both towards headwaters, between catchment production and transfer zones, as well as in lowland reaches where they form major long-term depositional sites (Petts, 1979; Williams and Wolman, 1984; Kondolf, 1997). Consequently, sediment transfer and planform adjustment is influenced by sediment continuity and discontinuity in zones upstream or downstream of waterbodies (Fig. 2.1).

However, waterbodies are not present in all upland catchments. In upland catchments where no waterbodies are present, the transition from the headwater zone to the transfer zone can be defined where the channel becomes topographically unconfined, channel slope decreases and planform changes from cascade or mountain torrent to straight, meandering or pool-riffle sequence. In these catchments, sediment continuity will be uninterrupted. Therefore, it is expected that sediment continuity and planform adjustment will differ in catchments with and without waterbodies.

The movement of coarse sediment in and between the stores of the USC has been compared to a 'jerky conveyor belt' (Ferguson, 1981; Newson, 1997) where sediment is transferred and stored over a range of temporal scales and moves in slugs, pulses or waves (Church and Jones, 1982; Reid et al., 1985; Nicholas et al., 1995). Sediment stores can release or buffer downstream sediment transport rates in response to exogenic or endogenic forcing, and therefore sediment can move at different spatial scales, intermittently through the USC impacting channel planform. For example, meso-scale slugs (wavelength 10^{-1}-10^{2} m) have no or very minor impact on channel planform creating local particle clusters or riffles, macroscale slugs (wavelength 10^{1}-10^{3} m) involve minor planform adjustments such as bar reorganisation, megaslugs (wavelength $>10^{3}$ m) result in channel adjustment such as bar accretion, bend adjustment, bar reorganisation; and superslugs (catchment scale) involve major valley floor adjustment (Hoey, 1992; Nicolas et al., 1995). Historical analysis of channel planform adjustments over the last 150 years can be used to identify changes in sediment dynamics and the passage of sediment through the USC (Wishart, 2004).

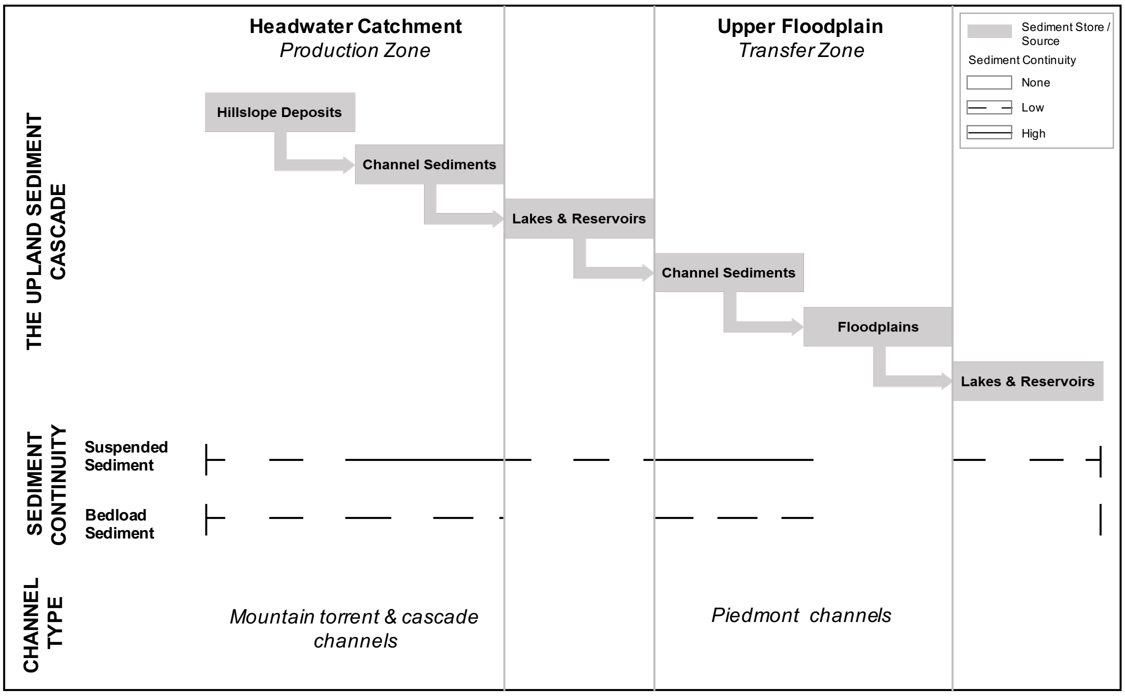


Figure 2.1. The upland sediment cascade (USC) framework displaying sediment stores and the relative sediment continuity through each store during non-flood conditions. In this thesis, the USC framework is modified from Schumm's (1977) simple sediment cascade model.

In Figure 2.1, the USC production zone is characterised by mountain torrent and cascade first and second order channels that have steep slopes (>0.03-0.30) and surrounding hillslopes (>0.15-0.7) (Montgomery and Buffington, 1993). Channels are categorised as longitudinally and laterally disorganised, with large boulders forming step pool like structures in the channel (Montgomery and Buffington, 1993). Here, channels are confined by the local valley topography and have no intervening floodplain; hillslopes are strongly (>80%) coupled to the channel (Lewin, 1981; Montgomery and Buffington, 1993; Harvey, 2001; Korup, 2005; Crozier, 2010). Sediment flux in this zone is via both suspended sediment and bedload transport (Johnson et al., 2001; Johnson et al., 2008), coarse sediment stored on hillslopes can be mobilised during heavy rainfall events, thus contributing to the total sediment load (Ashbridge, 1995). Hillslope erosion processes (mass wasting or water-driven) are the principal sources of sediment, which is deposited either on the hillslopes or in the channel (Montgomery and Buffington, 1993; Fuller et al., 2016). Consequently, planform adjustments are limited in this zone due to topographic confinement and are associated with vertical bed incision or transfer of large boulders during large magnitude flood events (Johnson and Warburton, 2002).

Previous studies have explored sediment dynamics in the USC production zone at the reach and channel scale including: (i) hillslope-channel coupling relationships (Harvey, 2001, 2007; Johnson et al., 2008; Smith and Dragovich, 2008; Caine and Swanson, 2013); (ii) variability in sediment supply, transfer and deposition (Johnson and Warburton, 2006); (iii) response of these systems to extreme flood events (Johnson and Warburton, 2002); and (iv) the relative contribution of sediment sources to the channel through a sediment budget approaches (Warburton, 2010). These studies provide a detailed understanding of sediment transfer and deposition in the production zone of the USC, however, few compare sediment dynamics between the production and transfer zone, or between upland catchments over the past 150 years. The aim of this thesis is to capture planform adjustments and sediment continuity spatially through the upland sediment cascade zones between multiple catchments over the last *c.* 150 years.

In the transfer zone (Fig. 2.1), sediment sources and deposits differ from those of the production zone as the channel (or piedmont channel) gradient decreases (slopes of <0.001-0.03), floodplain width increases, and the channel becomes unconfined allowing greater channel-floodplain interaction (Lewin, 1981; Church, 2002). Channels in the transfer zone typically have Strahler (1952; 1957) stream orders ≥ 3, display riffle-pool and meandering planforms with active and vegetated bars. Hillslope erosion processes are largely disconnected from the active channel by floodplains and therefore do not contribute directly to channel sedimentation (Lewin, 1981; Newson, 1981; Church, 2002). Instead, sediment in this zone is sourced from tributary inputs and reworked from the channel bed or banks. Suspended sediment dominates the low to medium flow sediment fluxes, with bedload sediment stored in the channel only mobilised at 50 - 60 % of bankfull flow (Carling, 1988; Knighton, 1998; Fuller et al., 2002). Only during overbank flow is the largest bedload sediment entrained in any quantity in this zone (Carling, 1988). Sediment continuity in the transfer zone is heavily influenced by anthropogenic modifications to the system (Fryirs et al., 2007; Lewin, 2013).

The presence of upstream reservoirs or impoundments disrupt coarse sediment supply from headwaters, and influence the potential for sediment transport downstream through flow regulation in the transfer zone (Petts and Thoms, 1986; Kondolf, 1997). For example, Petts (1980) showed that channel capacities on five impounded rivers in the Scottish Southern uplands were reduced to between 0.16 and 0.54 of their pre-impoundment capacity. This results in sediment aggradation and channel narrowing (Gilvear, 2000). In addition, many upland rivers in the transfer zone have become 'genetically modified' over time (Lewin, 2013) with channels artificially confined by flood protection structures to safeguard adjacent land, reducing channel-floodplain interactions. Channel confinement and embankments disconnect the sediment supply, narrow the channel enhancing stream power locally (Surian and Rinaldi, 2003). For example, on the River Tay in Scotland, flood protection embankments built in the 19^{th} and 20^{th} centuries modified multichannel wandering gravel bed river sections to narrower single-channel reaches, with limited lateral migration (Gilvear and Winterbottom, 1992). Consequently, sediment continuity and potential for sediment storage and planform adjustment in the transfer zone is modified and reflects a legacy of anthropogenic activity over the period of measurable change (Wohl, 2015).

The USC provides a useful framework for understanding sediment continuity and planform typologies and potential for adjustment through the stream order hierarchy. However, few studies have explored planform adjustments or compared river behaviour between production and transfer zones over the period of measurable change at the reach, catchment or regional scale. This thesis aims to address this by exploring reach, catchment and multiple catchment spatial variability in planform adjustment and sediment continuity over the last *c.* 150 years in an upland region. To understand sediment continuity through the USC it is important to understand the exogenic and endogenic controls.

2.3 Exogenic and endogenic factors influencing planform adjustment

To understand the spatial and temporal patterns of river planform adjustment types it is important to discuss the exogenic and endogenic factors controlling water and sediment discharge across a catchment (Fig. 1.2, Chapter 1). Exogenic controls include climate, geology, topography, vegetation and anthropogenic activity; endogenic controls include discharge, stream power, sediment transfer, erosion and deposition (Figure 1.2, Chapter 1). Endogenic processes can create 'endoslugs' which describes the transfer of sediment sourced from the riverbed or bank erosion caused by flows above the critical entrainment threshold (Wathen and Hoey, 1998). In contrast 'exoslugs' are generated by an addition of sediment from external sources to the river such as slope failures, or anthropogenic activities such as mining (Knighton, 1989). This section (Section 2.3) describes the exogenic controls influencing endogenic processes and planform adjustment and stability. This section begins by exploring the exogenic controls: climate, geology, anthropogenic activity and land cover (Section 2.3.1 – 2.3.4). The second section (Section 2.3.5) explores the impact of exogenic controls on endogenic processes: sediment supply, transfer and deposition.

2.3.1 Climate

Climate is an exogenic control and determines precipitation quantity and intensity, which influences endogenic processes: river discharge, flood frequency and magnitude (extreme events), stream power and therefore the potential for sediment erosion, transfer and deposition (Newson, 1980a; Wolman and Miller, 1960; Milne, 1982; McEwen, 1994; Rumsby and Macklin, 1994). High magnitude, low frequency flood events can cause riverbed and bank erosion, transport high quantitates of sediment over short time periods (hours) and are therefore often viewed as the principal mechanism driving planform adjustment (Leopold and Maddock, 1953; Rumsby and Macklin, 1994; Joyce et al., 2018; Joyce et al., 2020). For example, hydraulic geometry theory (Leopold and Maddock, 1953) states that channel planform is governed by a dominant discharge, e.g. bankfull discharge (Ackers and Charlton, 1970). In the upland Howgill Fells, Cumbria, Harvey (1991) found a positive relationship between discharge and channel width. However, Wolman and Miller (1960) proposed that the range, magnitude and frequency of flow events are important in promoting channel change. For example, frequent, low-magnitude flow events can have an equal control on channel morphology, which are often disguised in power law relationships (Lane and Richards, 1997). Pickup and Warner (1976) found that the most effective discharges with regard to bedload transport occurred 2-5 times a year and were the small frequent flows (1.58 – 2 year return flood (natural bankfull discharge)). Understanding the link between climate and discharge is therefore important for interpreting the pattern and controls of river planform adjustment over the last *c.* 150 years, which is discussed in this section.

Atmospheric circulation patterns have been linked to the occurrence of flood events and planform adjustments (Rumsby and Macklin, 1994; Rumsby and Macklin, 1996; Werritty and Leys, 2001). Rumsby and Macklin (1994) studied the relationship between zonal (westerly) and meridional (easterly) weather patterns on flood frequency and magnitude on the River Tyne, north-east England. High frequency major (>20 year return period) and moderate (5 - 20 year return period) floods occurred during meridional periods and caused river bed incision. Meridional circulations were associated with higher-intensity precipitation, lower rates of evapotranspiration and therefore higher soil wetness, which promoted rapid runoff and large flood peaks (Rumsby and Macklin, 1994; Pattinson and Lane, 2012). In contrast, flood-poor periods occurred during zonal and intermediate phases (no dominant circulation pattern) and were characterised by lateral river reworking (Rumsby and Macklin, 1994). Rumsby and Macklin (1994) observed river metamorphosis during flood-rich periods on Thinhope Burn and Broomhaugh islands piedmont zone, however, this pattern of adjustment is also attributed to a legacy of mining activity in the catchments acting as a major 'exoslug' supply of sediment to the channel during flood-rich periods, increasing the sensitivity of the system to change (Rumsby and Macklin, 1994). Therefore, planform adjustments can occur in response to multiple exogenic controls.

Werritty and Leys (2001) explore changes in channel planform on nine Scottish upland piedmont rivers in the transfer zone of the USC, in response to flood-rich and flood-poor periods over 250 years. Rates of lateral channel adjustment and gravel bar reworking coincided with the occurrence of flood-rich periods (Werritty and Leys, 2001). However, the scale of reworking was less dramatic than the reported planform adjustments (metamorphosis) identified in catchments in northern England by Rumsby and Macklin, (1994). This is attributed to differences in land use, with the Scottish rivers being weakly coupled to the surrounding valley hillslopes and relatively coarse glacial sediment beds (Werritty and Leys, 2001). Therefore, in the Scottish upland example, rivers demonstrate a 'robust behaviour' with only internal adjustments in their planform in response to flood-rich periods (Werritty and McEwen, 1997).

Pattison and Lane (2012) plot flood-rich and flood-poor periods for the upland river Eden catchment, Cumbria, north-west England, and link flood occurrence to Lamb weather types. Flood-rich periods were identified between 1873–1904, 1923–1933, and 1994 onwards (Pattison and Lane, 2012). Of the 27 objective Lamb weather types (Lamb, 1950), only 11 could be associated with the extreme floods during the gauged period, and only 5 (cyclonic, westerly, south-westerly, cyclonic-westerly, and cyclonic south-westerly) of these accounted for >80% of recorded extreme floods (Pattison and Lane, 2012). The periods of extreme floods also align with periods of a strong positive NAO index (Wilby et al., 1997). Flood-rich and flood-poor periods and the links to Lamb weather types are not nationally synchronous (Macdonald, 2006; Macdonald et al., 2010; Macdonald and Sangster, 2017). Regional and catchment scale characteristics, for example orographic rainfall controls, rain-shadow effects and the distance from oceans (Dixon et al., 2006) can influence local climate variability. In addition, local catchment characteristics, anthropogenic activity and antecedent conditions means geomorphic response can differ amongst catchments in response to changes in climate and precipitation events (Pattison and Lane, 2012). Therefore, the link between climate and the frequency and magnitude of floods and subsequent planform adjustments can vary between catchments in the same region.

More recently, palaeo floods have been reconstructed using lake sediment cores from Bassenthwaite Lake, Lake District, UK (Chiverrell et al., 2019). In the Lake District, recent flood events (2005, 2009, 2015) and associated planform adjustments were unprecedented in the 558 year palaeo record (Chiverrell et al., 2019). The flood-rich periods are non-stationary in their correlation with climate indices, but a 1990 – 2018 flood rich period is associated with warmer Northern Hemisphere temperatures and positive Atlantic multi-decadal oscillations (Chiverrell et al., 2019).

Climate is commonly believed to indirectly influence river planform through variations in precipitation influencing discharge and stream power (Newson, 1980a; Wolman and Miller, 1960; Milne, 1982; McEwen, 1994; Rumsby and Macklin, 1994). However, Blacknell (1981) measured channel bank erosion on an upland river in Wales, and linked the temporal pattern to precipitation and the number of days in a month in which air frost was recorded. The rate of river bank erosion increased in response to an increase in the number of frost days in January 1979, immediately following two months of relatively high rainfall (Blacknell, 1981). Freeze-thaw processes can aid removal of material from non-cohesive banks. Therefore, temperature plays a secondary influence on bank stability and the potential for planform adjustment after precipitation input.

Climate determines precipitation quantity and intensity, which influences endogenic processes: river discharge, flood frequency and magnitude stream power and therefore is important for influencing sediment erosion, transfer, deposition and planform adjustment. Flood-rich periods have been associated with changes to river channel planform (Werritty and Leys, 2001; Pattison and Lane, 2012). However, the link between climate and flood-rich periods can vary between catchments regionally due to local system characteristics (e.g. land use, channel hillslope coupling) and orographic rainfall effects. This research will investigate the influence of low frequency, high magnitude flood events on river planform at the reach, catchment and multiple catchment scale in an upland region over the last 150 years (research question 3).

The following sections discuss the influence of geology, glaciation, anthropogenic activity and land cover on sediment continuity and channel stability.

2.3.2 Geology and glacial legacy

In upland regions, the catchment topography is conditioned by the underlying geology and glacial legacy (Newson, 1981; Cienciala et al., 2020). Geology sets the availability of sediment and type of channel, i.e. bedrock or alluvial systems and therefore the potential for channel planform adjustment (Schumm, 2006). In the UK, Quaternary glaciations created confined and unconfined U-shaped valleys, eroded valley sides and floors depositing unconsolidated sediment setting the source of material for transport by rivers (Newson, 1981). The geology and glacial legacy sets the USC structure (Fig. 2.1), which influences the location of channel planform types, potential for adjustment and sediment supply, transfer and deposition (Wilson, 2010).

The topography influences the potential for river adjustment and the coupling of sediment sources to the river channel (Harvey, 1991; Harvey 2001; Fryirs, 2007; Fryirs et al., 2013). Playfairs law (Playfair, 1802) states river size will be proportional to the size of the valley; hence valley confinement will influence the potential for the river channel to migrate and avulse (Lane and Richards, 1997; Whiting and Bradley, 1993; Fryirs et al., 2016; Cienciala et al., 2020). For example, first and second order channels in catchment headwaters (production zone of USC) are often topographically confined and therefore it is expected that these channels will display little 2D lateral adjustment to channel banks. Instead, adjustments in these channels will be bar adjustment, or vertical bed incision over the period of measurable change (Milne, 1983a,b; Montgomery and Buffington, 1993; Downs and Gregory, 1993). In contrast, where channels are laterally unconfined, channels can interact with floodplains as there is accommodation space for adjustments, such as avulsions (Schumm, 1977; Church, 1996; Ibisate et al., 2011).

Figure 2.2 shows an example of hillslope and valley channel coupling in the upland Carlingill valley, in Howgill Fells, north-west England (Harvey, 2001). In the channel headwaters, mass wasting events can deliver sediment directly to the channel episodically at the event scale, or material can be stored and released intermittently to the channel from debris cones or alluvial fans (Fig. 2.2), (Harvey, 1991; 2000). Downstream, in the floodplain valley transfer zone of the USC, channels become disconnected from the hillslopes and therefore the main sediment sources are from channel floodplains and banks through lateral reworking during bankfull and over-bank flows (Fig. 2.2).

2.3.3 Anthropogenic Activity

Anthropogenic activity is an exogenic control, and can alter river discharge, sediment supply and can directly change channel planform and therefore influence the potential, frequency and type of planform adjustment spatially and temporally through the USC (Sear et al., 2000; Downs and Gregory, 2004; James and Marcus, 2006; Macklin and Lewin, 2008; Macklin et al., 2014; Gregory, 2019).

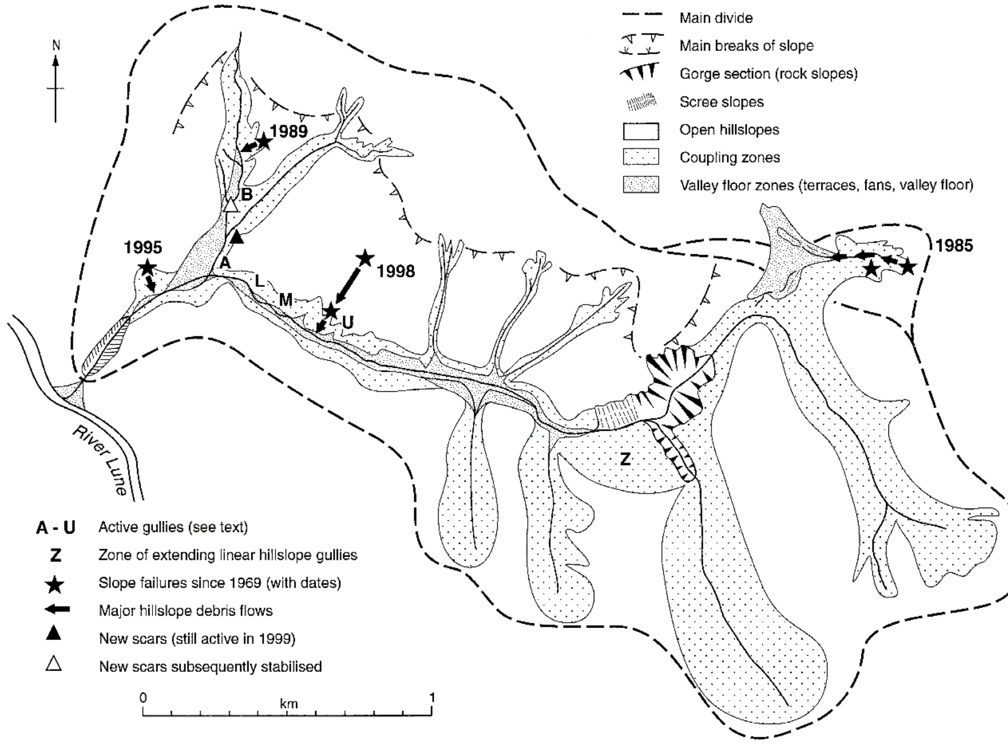


Figure 2.2. Sediment coupling zones across the USC demonstrated in the Carlingill catchment, north-west, England. Source: Harvey (2001).

Anthropogenic activities have been impacting fluvial systems both directly and indirectly for thousands of years (Downs and Gregory, 2004; Higgitt et al., 2001; Lewin et al., 2010) via river channelization, water abstraction, flow regulation, mining, agriculture, urban development and channel redesign and restoration (Lewin, 2013), examples of these modifications are summarised in Table 2.1. As a result, many upland catchments are 'genetically modified' (Lewin, 2013). Despite the fact that some anthropogenic activities have reduced or ceased in UK uplands over the last 1000 years (e.g. mining, deforestation), effects of anthropogenic activity can have lasting legacies, which rivers are still adjusting to in response (Wohl, 2019). Therefore, it is important to be aware of anthropogenic activities occurring both over the last *c.* 150 years and longer timescales when interpreting the patterns of planform adjustment and stability.

2.3.3.1 River channel management and maintenance

River channels have been directly and indirectly modified since the medieval period to protect land, homes and infrastructure from flooding, to prevent riverbank erosion, make rivers navigable and for land drainage (Vaughan, 1610; Taylor, 1864; Grantham, 1859; Smith, 1910; Brookes 1988), Table 2.1. The Land Drainage Act (1861) and subsequent revisions of this legislation have enforced the management of river systems (Brookes, 1988). For example, in 1927, a Royal Commission on Land Drainage in England and Wales reported that "rivers under 'modern' conditions of roofing, paving roadmaking sanitation and agricultural underdrainage were selected to create discharge functions for which they were not designed by nature" (Brookes, 1988). Therefore, rivers were often modified (straightened, dredged, Tables 2.1, 2.2) to make them suitable for modern day living. The Land Drainage Act (1930s) and subsequent River Boards Act (1948) further highlighted the importance of maintaining and documenting river management across the UK. The Water Resources Act of 1963 established regional water authorities, which was superseded by the Water Act 1989 in which management was led by National River Authorities (1989 – 1996). The National River Authorities have since has been superseded by the Environment Agency who currently manage and maintain these systems across catchment partnerships and rivers trusts. Channel management has historically involved hard-engineering approaches (e.g. embankments, bank rock armour), soft-engineering 'green' solutions (i.e. tree planting) to more recently, river restoration schemes (Sear, 1994; Wohl et al., 2005; RRC, 2013; Williams et al., 2020).

River 'channelization' is defined as a form of channel management where a river is straightened, re-sectioned, banks are reinforced, embankments are built or the channel is cleared and maintained, definitions of these terms are listed in Table 2.2 (Brookes, 1988; Knighton, 1988). Engineering works alter endogenic processes: stream power, sediment continuity and lateral floodplain interaction (sediment supply) and therefore the potential for planform adjustment (Petts et al., 1989). For example, river straightening decreases the channel length (by reducing sinuosity) and therefore increases channel slope, velocity and sediment transport capacity (Brookes, 1985). Downstream of straightened reaches sediment is deposited as the sediment transport capacity is reduced, sediment deposition promotes flow divergence to banks causing subsequent riverbank erosion (Brookes, 1985). Dredging lowers the riverbed level, causing upstream migration of bed incision (knick-point migration) (Kondolf, 1997), increases channel bank height, which triggers bank erosion leading to lateral channel instability (Sear and Archer, 1998). Channelization works have often been piecemeal, at the reach scale on high stream order channels in the floodplain valley transfer zone of the USC. Piecemeal approaches are often ineffective because they fail to understand the spatial and temporal patterns of sediment transfer through the USC. Therefore, the approach is unsustainable providing only a localised, short-term fix (Gurnell et al., 2015). Hence, the challenge is to better understand the interaction of sediment and flow on channel planform at the reach, catchment and regional scale in upland environments to better inform and target sustainable management actions (Gilvear, 1999; Winterbottom, 2000; Hoffman et al., 2010; Brierley and Fryirs 2016).

Table 2.1. Anthropogenic developments and modifications to rivers over time (modified from Downs and Gregory (2004)).

Time period	Anthropogenic developments	River management methods
Pre-industrial revolution	Flow regulation Drainage schemes Fish weirs Water mills Navigation	Land drainage In-channel structures River diversions Dredging Local channelization
Industrial revolution (1800s)	Industrial mills Cooling water Power generation Irrigation Water supply	Dam construction Canal building River diversions Channelization
Late 19th century – mid 20th century	Flow regulation Flood defences	Dam construction Channelization River diversions Structural revetments River basin planning
Mid 20th century	River flow regulation Integrated river use projects Flood control Conservation management Management of rivers	Dam construction River basin planning River diversions River restoration
Late 20th century and early 21st century	Conservation Restoration Rewilding	Catchment based river management and planning Mitigation, enhancement and restoration techniques

Table 2.2. River channelization methods (based on Nunnally and Keller, 1979; Knighton, 1998).

Method	Definition
Straightening	River is shortened by artificial cutoffs, steepening the gradient and increasing flow velocity.
Resectioning	Widening and/or deepening of the river channel to increase its conveyance capacity and therefore reduce the incidence of overbank flooding.
Embankments	Channel banks are artificially raised, or embankments are constructed along the river banks to confine floodwaters.
Clearing, snagging, dredging	Removal of obstructions / sediment from the channel to decrease resistance and increase capacity and flow velocity.

On the upland river Tay, Scotland, flood embankments and channel straightening confined a previously braided channel to a stable single channel through the 19th and 20th century (Gilvear and Winterbottom, 1992; Gilvear, 1993). Flood embankments have also reduced channel braiding on the Rivers Tummel and Tay (Winterbottom, 2000) and the River Dee (McEwen, 1989). However, despite bank protection the previously braiding zones are still susceptible to planform adjustment causing flood embankments to be breached, channel shifts and the development of gravel bars during flood events as the channel attempts to adjust to a pre-disturbed condition (Gilvear and Winterbottom, 1992; Gilvear, 1993). This example highlights how anthropogenic activity can alter natural sediment continuity and therefore planform adjustment.

Many channelization schemes are poorly documented and took place prior to the first Ordnance Survey (OS) map of England in the early 19th century (Winterbottom, 2000) and therefore it can be difficult to identify modified channels from available historic data. However, channelized rivers often have distinctive characteristics (Table 2.2) such as uniform straight planforms, little mature vegetation, or vegetation of a similar age, and reinforced banks with artificial materials and can be identified from air photographs or field site visits.

River management has shifted from hard engineering channelization projects to more sustainable river restoration schemes in the 21st century (Table 2.1). River restoration schemes aim to restore the natural functioning of river systems that channelization and land management practices might have reduced (Sear, 1994; Wohl et al., 2005; Beechie et al., 2010; RRC, 2013; Grabowski et al., 2014; Williams et al., 2020). Restoration schemes can involve modifying channel planform shape, including: re-meandering previously straightened rivers, removing artificial structures, installing woody debris and pool-riffle sequences to improve the geomorphic diversity, natural functioning and create habitats (Sear, 1994; Kronvang et al., 1998; Wohl et al., 2005; Beechie et al., 2010; Kondolf, 2011; RRC, 2013). For example, the Allt Lorgy, a tributary of River Dulnain within the Spey catchment, Scotland, had been historically realigned (straightened), with extensive raised embankments, dredging and boulder bank and toe protection, this lead to channel bed incision and a decrease in geomorphic heterogeneity (Williams et al., 2020). Restoration of the channel involved removing the artificial bank protection and allowing the channel to laterally migrate and develop natural wandering pool-riffle sequence (Williams et al., 2020). Four years after restoration, lateral channel migration and associated bank erosion enabled the formation and maintenance of lateral and point bars, riffles and overall, the spatial extent of in-channel geomorphic units increased by 31 % (Williams et al., 2020). Consequently, rivers in the UK have a legacy of channel management, including channelization and more recently river restoration over the era of measurable change through the stream network hierarchy. Understanding the history of channel management works is important for interpreting the patterns and controls of river channel planform adjustment to assess if they are natural or artificial.

2.3.3.2 Lakes, dams and impoundments (flow regulation)

Previous research has discussed the impacts of lakes, dams and impoundments downstream on flow regulation, sediment transport and channel planform in the USC transfer zone (Petts and Lewin, 1979; Gurnell, 1983; Williams and Wolman, 1984; Kondolf, 1997; Petts and Gurnell, 2005). Lakes, dams and impoundments act as long term or permanent sinks of sediment in the USC disconnecting the upstream sediment supply from downstream (Kondolf, 1997; Foster, 2010). As a result, directly downstream of reservoirs enhanced bed and bank erosion is often observed changing channel planform and gradient (Petts, 1979). Further downstream, regulated flows reduce the magnitude of peak flow events leading to sediment aggradation due to a reduction in sediment transport rates (Petts, 1979; Brewer et al., 2000). Shields et al. (2000) found that reduced frequency and duration of high flow events downstream of reservoirs reduced channel lateral migration rates by factors of 3 to 6. Channel response to dams and impoundments tend to be rapid after construction, however, over longer time periods of reduced flows planform adjustments tend to be progressive as they disrupt sediment continuity through the USC (Williams and Wolman, 1984). In the Lake District upland region, north-west England, water is abstracted from Thirlmere Reservoir, Ennerdale Water, Crummock Water, Haweswater, Kentmere Reservoir, Wet Sleddale Reservoir and Wast Water therefore rivers downstream of these lakes will be influenced by flow regulation.

2.3.3.3 Metal mining and gravel extraction

Metal mining has been occurring in the UK uplands since the Roman period (White, 1998). Metal mining intensified and began to influence river sediment yields and channel planform during the 18th and 19th century (Macklin, 1986; Higgitt et al., 2001; Warburton et al., 2002; Wishart, 2004). Hydraulic mining operations (hushing) (White, 1998), ore crushing (Bowes and Proud, 1984) and the erosion of spoil heaps can directly supply coarse and fine sediment 'exoslugs' to channels promoting changes in planform (Knighton, 1989; Wishart et al., 2008). In addition, the deposition of phytotoxic fine sediment from mines prevents riparian vegetation growth, reducing bank stability (Macklin and Lewin, 1989). The volume of water and sediment supplied to the channel depends on the proximity of the mine to the channel and the duration and intensity of extraction from the mine (Macklin, 1997). In Hudeshope Beck, Teesdale and Black Burn, northern Pennines, rivers show downstream channel and floodplain sedimentation as a result of direct episodic inputs of sediment from hushing operations (Macklin, 1997). However, in some locations sediment delivery to channels from mining activities can have little impact on channel planform as it is directly transported through the fluvial system (passive dispersal) (Lewin and Macklin, 1987; Taylor and Macklin 1998).

Gravel extraction has affected the planform of piedmont gravel-bed rivers in the UK since the 19th century (Newton, 1971; Sear and Archer, 1998; Archer, 2003; Wishart et al., 2008). River gravels provide a source of aggregate for building, and commercial extraction has taken place globally (Page and Heerdegen, 1985; Erskine et al., 1985). In Wooler Water, Northumberland, gravel extraction led to riverbed incision of 9 m and channel planform metamorphosis from a laterally active wandering gravel bed river to a single thread sinuous channel (Sear and Archer, 1998). However, the majority of planform changes that occur on reaches subject to gravel extraction coincide with high-magnitude, infrequent flood events (Sear and Archer, 1998).

Wishart et al., (2008) highlight the difficulty in identifying impacts of gravel extraction (1945-1960) on planform change from the analysis of historic maps and air photographs from 1844-1991 in the River Wear catchment, north-east England (Fig. 2.3). Figure 2.3 shows channel planform is braided from 1844 – 1919. Active gravel bar areas become vegetated and the channel transitions to a single thread channel with vegetated bars between 1951 – 1991 (Fig. 2.3), (Wishart et al., 2008). The transformation from multi-thread to single-thread channel coincides with the cessation of gravel mining but also a decline in flood magnitude across the catchment (Wishart et al., 2008). Therefore, there is an element of equifinality where channel planform adjustment could be a result of both changes in catchment scale climate dynamics or reach scale anthropogenic activity.

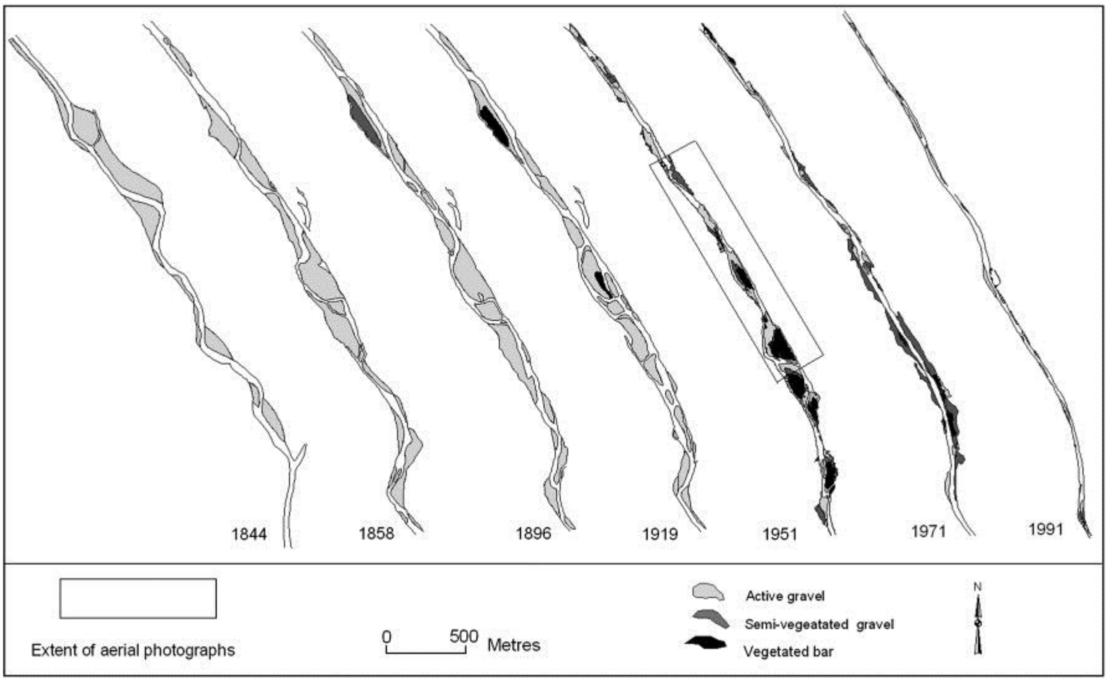


Figure 2.3. Channel planform changes at Harperley Park (1844 – 1991), River Wear catchment north-east England. Source: Wishart et al., (2008), flow direction is north.

2.3.4 Land cover

2.3.4.1 Vegetation

Both riparian and catchment-wide vegetation cover influences surface runoff and sediment availability to rivers (Hickin, 1984; Thorne et al., 1997; Gurnell et al., 2009). Riparian vegetation influences bank strength, bank resistance to flow and therefore overall bank stability (Hickin, 1984; Millar, 2000; Jang and Shimizu, 2005; Gurnell, 2014). Hey and Thorne (1986) found that UK river width at locations with densely vegetated channel banks were, on average, approximately 0.5 times narrower than that of weakly vegetated river banks. Millar and Quick (1993), found that well-developed bank vegetation increases bank stability, as a result these channels were narrower and deeper than un-vegetated channels, where erosion dominated. The presence of riparian vegetation therefore can influence the potential for bank erosion and sediment delivery to the river channel.

Anthropogenic activity can influence vegetation cover (afforestation and deforestation) at the reach, catchment and regional scale (Gurnell et al., 2018). Widespread deforestation across UK uplands during Mesolithic and Neolithic periods has coincided with phases of enhanced valley floor sedimentation (Davies and Turner, 1979; Evans, 1990; Macklin et al., 1991; Chiverrell, 2009; Hatfield and Maher, 2009a,b). Over the past 150 years the lack of forested upland headwater catchments has resulted in a decrease in rainfall interception and infiltration rates, therefore increasing surface runoff and sediment delivery to channels (Evans, 1990). In the USC, widespread vegetation clearance in channel headwaters can destabilise sediment which can be mobilised during high rainfall events and transported through catchment systems and deposited in floodplain valley transfer zone (Macklin et al., 1991). Marshall et al., (2013) demonstrate the impact of different vegetation covers on soil infiltration rates in upland Wales. On broadleaf tree covered plots surface runoff volumes were reduced by 78% and by 48% on un-grazed plots compared to grazed pasture plots (Marshall et al., 2013). Five years after tree planting, near-surface soil bulk density was reduced and median sol infiltration rates were 67 times greater in plots planted with trees compared to grazed pasture (Marshall et al., 2013). Vegetation can therefore influence sediment supply to channels which in turn influences planform stability.

In-channel large wood and log jams can influence sediment continuity and therefore river planform (Gregory et al., 1985; Piégay and Gurnell, 1997; Gurnell and Sweet, 1998; Sear et al., 2010; Polvi and Wohl, 2013; Picco et al., 2017). Large wood and log jams trap sediment, increase the channel flow resistance, resulting in accumulation of sediment and organic matter leading to changes in channel capacity (Jeffries et al., 2003; Curran and Wohl, 2003). Changes in channel capacity caused by large wood and log jams can also lead to an increase in the frequency of overbank flooding (Gregory et al., 1985; Brown, 1997; Jeffries et al., 2003). Wood is increasingly being used for in-channel restoration or natural flood management projects to improve modified and degraded rivers (RRC, 2013; Grabowski et al., 2019). Therefore, in the future in-channel wood has the potential to be an important reach scale control on planform adjustment (RRC, 2013; Grabowski et al., 2019).

2.3.4.2 Agriculture

Large scale forest clearance in the Mesolithic and Neolithic periods in the UK uplands made room for agricultural practices (Davies and Turner, 1979; Evans, 1990). Macklin et al., (2010) report an acceleration in floodplain sedimentation rates after *c.* 1000 BP linked to agricultural activities. Upland floodplains were modified by installing drainage ditches (open ditching, or piped under-drainage) or irrigation schemes to support agriculture (Newson, 1980b; Longfield and Macklin, 1999). Drainage ditches can increase the supply of water and sediment through ditch erosion to channels therefore influencing sediment loads and flood risk (Newson, 1980b). In Wales, Newson (1980b) found that catchments with land drainage had higher sediment yields compared to catchments without drainage, similar patterns have also been observed by Owens et al., (2002) in Scotland. Drainage ditches therefore alter the natural sediment regime which can lead to enhanced in-channel sedimentation.

Increases in river bank erosion have also been attributed to grazing in upland catchments (Evans, 1997; 1998; Orr and Carling, 2006; Lefrançois et al., 2007). It is estimated that 70 % of the total number of sheep in the UK graze in upland regions (Sansom, 1999). Grazing can reduce vegetation cover on riparian banks, leads to a thin impermeable layer in the soil A-horizon (Warren, 1986) and therefore reduces interception and evaporation (Sansom, 1999). Direct trampling of the river banks can also lead to increases in bank erosion and a decrease in bank stability (Trimble and Mendel, 1995). Therefore, in catchments that are grazed and have little mature tree or vegetation cover it is expected that the river banks will be more susceptible to bank erosion and channel planform adjustment, particularly during extreme flood events. Few studies have investigated regional scale patterns of planform adjustment in relation to different land cover types.

Table 2.3. Anthropogenic exogenic controls on hydrology, sediment continuity and planform adjustment (modified from Downs and Gregory, 2004).

Exogenic control	What changes might occur? Endogenic process change (Hydrology, H; sediment, S)	Channel adjustment (*clearly evident)
De-snagging and clearing	S+	*
Clearing of vegetation/trees	S+	*
Sediment removal (dredging/extraction)	S+	*
Sediment addition	S+	*
Afforestation	S-	*
Restoration	H- + S- +	*
Bank protection	H+ S-	*
Embankments and levee construction	H+	
Resectioning	H+-S-	*
Straightening	H+	*
Dam/ flow abstraction	H- S-+	*
Weirs	H-S-+	*
Bridge crossings	H+ S-	*
Deforestation	H+ S+	*locally
Land/agricultural drainage	H+	*locally
Mining	H+ S+	*locally
Grazing	S+	*locally
Urbanization	H+ S-	*

Sections 2.3.1 - 2.3.4 have summarised the main exogenic controls influencing the discharge, stream power, sediment transport (endogenic processes) and planform adjustment. Table 2.3 summarises the main exogenic controls and their relative impact on planform adjustment. Understanding the relative importance of the exogenic

controls and the influence on planform adjustment and stability is a focus of this research (RQ2).

2.3.5 Influence of exogenic controls on endogenic processes

Upland river planform adjustment and stability reflects the complex combination of interactions and feedbacks between exogenic forcing mechanisms and endogenic processes spatially and temporally (Fig. 1.2, Chapter 1). Climate is a primary catchment wide driver of discharge and therefore the potential for in-channel erosion, sediment transport and geomorphic change (Fig. 1.2, Chapter 1). The exogenic controls geology, topography, vegetation, anthropogenic activity and land cover regulate endogenic processes and the planform response to changes in climate (Newson, 1980a; Rumsby and Macklin, 1994). For example, low magnitude high frequency flood events can initiate planform adjustment (Leopold and Maddock, 1953), however the type of adjustment is influenced by the availability and coupling of sediment sources (Harvey, 1991), degree of topographic confinement governed by the geology, or anthropogenic activity and land cover. Consequently, sediment can move as exogenous (e.g. input of sediment from mining activities) or endogenic slugs (e.g. feedback between sediment supplied from the riverbed and banks) (Wathen and Hoey, 1998; Knighton, 1989) through upland systems resulting in planform adjustments (Macklin, 1986a). As a result, it can be difficult to discriminate a singular control of river planform adjustment or stability (Joyce et al., 2020). The following section (2.3.5.1) discusses endogenic responses to flood events through the USC and how they can be regulated by exogenic controls (e.g. anthropogenic activity, land cover).

2.3.5.1 Endogenic response to flood events in upland rivers

The temporal pattern of river planform adjustments in many upland catchments has been linked to the incidence and severity of major floods, which is governed by climate (Wolman and Miller, 1960; Anderson and Calver, 1980; Milne, 1982; McEwen, 1989; Rumsby and Macklin, 1994; McEwen, 1994; Werritty and Hoey, 2004). The geomorphic impacts of high magnitude, low frequency flood events can vary through the upland sediment cascade (Carling, 1986a, Harvey, 1986a, McEwen and Werritty, 1988; Milan, 2012; Joyce et al., 2018; Milan and Schwendel, 2019). In first and second order headwater channels, lateral channel planform adjustments are restricted due to topographic confinement. Instead, these channels can undergo bed incision and large boulders are transported during flood-rich periods (Carling, 1986; Johnson and Warburton, 2002).

In the transfer zones of the USC channels become laterally unconfined, and channels can laterally migrate and interact with the surrounding floodplains (Harvey, 1991; Werritty and McEwen, 1988; Joyce et al., 2018). Werritty and McEwen (1988) document the geomorphic impact of the August 1978 flood (1 in 50 year return period flood) on the upland river Allt Mor, Scotland. The Allt Mor, displays a mountain torrent form in its upper reaches, here, no or little evidence of flood impacts were observed as channel boulders were too large to be entrained (Werritty and McEwen, 1988). In contrast, downstream, where the channel becomes laterally unconfined in the floodplain valley transfer zone, shallow transitional landslides delivered sediment to the channel and bar re-organisation and lateral expansion occurred (McEwen and Werritty, 1988).

Similarly, in the floodplain valley transfer zone at Hoaroak Water (Exmoor, south-west England) the August 1952 flood (recurrence interval of over 150 years) caused widespread sediment deposition, filling in old channels causing channel avulsion, creating a new channel path (Anderson and Calver, 1977; Anderson and Calver, 1980). Since the flood event, the channel planform has remained relatively stable with little adjustment (Anderson and Calver, 1980; Werritty and Ferguson, 1980). In the north Pennines, Carling (1986) similarly identifies planform adjustment (avulsion, sediment deposition) in response to Noon Hill flash floods on valley floor sections. Therefore, the response to flood events is regulated by the availability of sediment and topographic confinement determined by the geology and glacial history.

However, not all channels display dramatic planform adjustment in response to flood events. For example, Winterbottom (2000) measured planform adjustments on reaches of the River Tay and Tummel, Scotland over last >25 and <250 years and show that channel planform adjustments are not reflected in the frequency and magnitude of flood events or discharge records, because of anthropogenic modifications (flow regulation and embankment construction) restricting planform adjustment. Wolman and Miller (1960) state that flood events can be physically geomorphically effective over short timescales, but low magnitude events may contribute to planform adjustments over longer timescales. Therefore, to understand the influence of climate, flood frequency and magnitude it is important that planform adjustments are viewed in the context of the period of measurable change and the collective exogenic controls are considered (Schumm and Lichty, 1965; Lane and Richards, 1998).

The identification of planform adjustment forcing mechanisms can be difficult as different endogenic or exogenic processes can cause the same planform adjustment response, a case of equifinality (Wishart et al., 2008). Previous studies have commonly focused on the influence of single endogenic or exogenic drivers of planform adjustment (Downs and Piégay, 2019) and not considered the multiple controls spatially across the USC. To understand the spatial patterns of planform adjustments it is therefore important to characterise the collective endogenic and exogenic controls operating at the catchment and reach scale and link them to historic planform adjustments (Joyce et al., 2020). In addition, planform adjustments may be immediate, lagged, progressive or permanent over a number of years after a flood event (Schumm and Lichty, 1965; Chappell, 1983; Dufour and Piégay, 2009; Piégay et al., 2020). Understanding the role of flood events on planform adjustment is important for understanding endogenic processes. This rationale constitutes the focus of research question 3 of this thesis: What is the influence of low frequency, high magnitude flood events on river planform at the reach, catchment and multiple catchment scale over the last 150 years?

2.4 Catchment and reach scale analysis of river planform adjustment and stability

Planform adjustment studies have commonly been focused at the reach scale (Schumm, 1969; Blacknell, 1981; Milne, 1982, 1983a,b; Lewin et al., 1977a; Lewin et al., 1977b; Lewin, 1977; Lewin and Hughes, 1976; Hooke and Yorke, 2010; Wishart et al., 2008; Warburton et al., 2002); many of these studies explore 3D patterns of adjustment the downstream response of a system to a perturbation such as flooding, or anthropogenic impact over time. Local, reach scale channel adjustments cannot be fully understood outside of the specific spatiotemporal context or related to other systems (Phillips, 2007).

Fluvial sediment budgets, quantify the erosion, deposition and transfer of sediment through a channel or reach over an event or time period (Rapp, 1960; Neill, 1987; Martin and Church, 1995; Reid and Dunne, 1996; Ashmore and Church 1998; Brewer and Passmore, 2002; Fuller et al., 2003; Joyce et al., 2018). The sediment budget approach assumes conservation of mass through a river reach and can be used to characterise 3D channel adjustments over time (Neill, 1987; Slaymaker, 2003). However, sediment budget approaches require detailed morphological data and hence are usually limited to small spatial (reach) scales (Neill, 1987; Reid and Dunne, 1996). More recently, volumetric changes in river channel planform have been much more readily identified using high resolution digital elevation models (DEMS) to construct DEMS of difference (Milan et al., 2007; Wheaton et al., 2010; James et al., 2012). DEMS of difference can be produced by subtracting one elevation model from another to identify erosion and deposition within a channel (Wheaton et al., 2010; James et al., 2012). The period over which volumetric changes in erosion and deposition is mapped is dependent on the temporal availability of the DEMS (e.g. last 20 years). DEMS of difference provide a detailed quantification of volumetric adjustments however, are limited by the time period of available data, the frequency of data capture, resolution of the data and spatial coverage, which is often focused on high order channels omitting headwater streams (Lane et al., 2003; James et al., 2012; Wheaton et al., 2013).

Graf (1984) proposed a 2D probabilistic approach to assess spatial patterns of river erosion; where the probability of erosion is directly proportional to the size of annual floods and inversely proportional to the distance upstream and distance laterally to the channel. Historic maps of river planform are converted to a series of cells, with each cell representing a 'channel' or 'non-channel' element, the change from channel to non-channel between two dates indicates erosion (Graf, 1984). The approach enables probability of 2D lateral erosion and avulsion to be identified on a reach using historic maps. It assumes that flood events are the main driver of river planform adjustment and it cannot differentiate the role of other multiple interacting endogenic and exogenic variables (e.g. land cover, anthropogenic activity) influencing sediment continuity and channel planform change. Deposition associated with erosion and channel migration is not explicitly captured in this method; and the accuracy of the estimated spatial probability model requires multiple epochs of channel planform mapping to define meaningful behaviour patterns.

It is therefore necessary that methodologies place reach scale temporal studies in the perspective of the wider catchment and regional context (considering multiple endogenic and exogenic controls), this will enable a synoptic understanding of the type of adjustment, whether adjustments are typical or anomalous and will allow comparisons between catchments. A wider spatial (catchment and, regional, multiple catchment and temporal assessment of river planform adjustments can be achieved by using historic maps and more recent air photographs taking a 2D approach. This rationale constitutes the focus of research question 1: How do river planform adjustments vary spatially across multiple catchments in a region over the last 150 years?

Macklin et al., (1998) state small-scale and short-term studies of river adjustments may be misleading as rivers need to be understood in terms of wider catchment and regional context. Macklin et al. (1998) digitise channel banks and gravel bar changes along an 85 km length main river in the Tyne catchment, UK from maps (1850) and aerial photographs (c. 1975). The Tyne study shows the timing of river instability is primarily related to climate controlled changes in flood frequency and anthropogenic modifications, with unstable reach locations determined by valley floor morphology. Hooke and Redmond (1989a) similarly showed that spatial scale was important and surveyed old OS maps between 1870 – 1950s for main upland rivers in England and found 35 % show some pattern of instability. Brewer et al., (2000) compare changes in digitised river planform and gravel bar area for 8 main trunk rivers in Wales from 1940 – 1990 to look at how changes vary over different scales. These examples are useful in documenting channel adjustments at larger spatial scales, however the studies are concentrated in the transfer zone on higher stream order channels and therefore omit low order channels from the USC headwaters. Furthermore, they do not address the significance of channel adjustment in relation to the wider multiple exogenic forcing mechanisms.

Fluvial audits provide a useful field and desk-based (review of historic maps) framework for categorising sediment source, transfer and depositional zones and have been applied widely across the UK on high order channels (Sear et al., 1995; Environment Agency, 2005). However, the approach involves detailed field reconnaissance, performed by experienced geomorphologists and therefore can be time consuming and difficult to apply beyond the reach scale. The approach also focuses on high order channels and does not capture the types of river changes in headwater areas and at the multiple catchment (regional) scales (Wallerstein et al., 2006).

More recently, Wishart (2004) presents a reach and catchment scale assessment of the temporal patterns of channel adjustment in upland rivers in the River Wear and River Tees catchment, UK. The results show that differences in planform adjustment patterns reflect the importance of specific catchment controls (e.g. bedrock) and reach controls (e.g. anthropogenic activity), (Wishart, 2004). Anthropogenic activity is a significant control over decadal time scales, whereas the frequency of flood events determines channel planform over centennial timescales (Wishart, 2004). Lisenby and Fryirs (2016) similarly explore channel changes at large spatial scales across trunk channels in 3 tributary basins of the Lockyer Creek catchment, Australia, and link the type of channel adjustments to catchment area, width:depth ratio and channel slope. They find that adjustments occur where catchment areas are between 10% - 60% of the total drainage area, with width:depth ratio and stream power influencing channel type (Lisenby and Fryirs, 2016). These studies highlight the added value of spatial and temporal assessments of channel planform adjustments that can be used to understand reach and catchment scale controls on sediment continuity.

However, existing planform adjustment studies focus on high order main channels, omitting smaller low order channels that can be a major source of sediment (Wishart, 2004; Lisenby and Fryirs, 2016). In addition, the methods developed are locational specific, for example, Lisenby and Fryirs (2016) extract geomorphic characteristics at points positioned along the river channel network spaced with an arbitrarily defined distance. This means the methodology cannot easily be transferred or applied to other settings or to the entire channel network where river lengths differ and results cannot easily be compared. Previous studies often focus on singular or a specific set of exogenic controls based on field or remote sensing data (Lisenby and Fryirs, 2016). Remotely sensed datasets now allow the collective exogenic controls discussed in Section 2.3 to be quantified at the catchment and regional scale (e.g. land cover, river management, geology, topography), (Gilvear and Bryant, 2016; Piégay et al., 2020). Consequently, there is a current lack of standardised method that quantifies channel planform adjustment and exogenic and endogenic controls over large spatial and temporal scales (Hooke, 1980; Lawler, 1993; Peixoto et al., 2009; Rowland et al., 2016). This lack of methodological consistency restricts comparisons between catchments in similar regional settings (Rowland et al., 2016).

2.5 Chapter Conclusions

The aim of this research is to quantify the spatial and temporal patterns and geomorphic characteristics of upland river planform adjustments over the past 150 years. This Chapter has presented an overview of the current understanding of the controls of planform adjustment and stability and discussed existing research at the reach and catchment scale. However, gaps in knowledge remain, to date:

1) The fluvial system is commonly categorised into distinct zones of sediment erosion, transfer and deposition: the 'simple sediment cascade' (Schumm, 1977). However, in upland regions, the sediment cascade is more complex, with sediment episodically sourced, transferred and deposited over different timescales. This behaviour has rarely been quantified in all zones of the USC over the last 150 years.
2) Upland regions are commonly defined as 'geomorphically active' (Hooke and Redmond, 1989a; Wishart, 2004); however, few studies have quantified planform activity at the catchment or regional scale over the last 150 years in upland regions.
3) River adjustment studies primarily focus on 3D approaches (e.g. DEMS of differencing, sediment budgets, fluvial audits) at small spatial (e.g. reach) or short temporal scales (e.g. event). Upscaling 3D approaches to the headwater channels at the catchment or across multiple catchments is resource and time intensive. 2D historic map and air photograph comparisons provide the opportunity to explore sediment continuity from

source to sink at wider spatial (multiple catchments) and longer temporal scales, however this has rarely been assessed in detail.

4) There is a lack of standardised methodology that quantifies channel planform adjustment and the collective exogenic and endogenic controls from channel headwaters to lowland sinks over the last 150 years in upland regions. Previous studies focus on planform adjustments in response to singular exogenic controls (e.g. flood events, or anthropogenic activity).
5) The influence of low frequency, high magnitude flood events on river planform at the reach, catchment and multiple catchment scale over the historical observational period (last 150 years) needs further investigation to identify if it is the dominant driver of planform adjustment in upland regions.

Hence, the spatial and temporal pattern of planform adjustments at the reach, catchment and regional scale and links to multiple exogenic and endogenic controls remains to be fully evaluated. This thesis:

1) Presents a reach (Chapter 4), catchment (Chapter 5), and multiple catchment (regional), (Chapter 6) assessment of the patterns of planform adjustment and stability over the past 150 years.
2) Develops and applies a systematic methodology to quantify the spatial patterns of 2D planform adjustment (Chapter 5 and 6) and the geomorphic controls. The methodology developed is based on analysis of remotely sensed datasets so that it can easily be applied to other upland settings.
3) Investigates the influence of flood rich periods on the occurrence of planform adjustment and stability at the reach, catchment and regional scale (Chapter 4, 5 and 6) to assess if flood events are the dominant driver of sediment continuity and planform adjustment over the period measurable change through the USC.

The upland sediment cascade is presented as an important framework for understanding sediment continuity and potential for river planform adjustments in upland regions. Therefore, the results, Chapters 4, 5 and 6 are framed within this context. Chapter 3 presents the upland study site in which this research will be focused on.

Chapter 3

Characteristics of the Lake District upland study site

3.1 Chapter summary

This chapter describes the characteristics: regional geology, topography, glacial legacy, prevailing climate and anthropogenic activity in the Lake District upland region, north-west England. The Lake District is chosen as a suitable case study to investigate the complexities and controls of historic upland channel planform adjustment and stability outlined in Chapter 1 and 2 because:

1) there is an active fluvial system where planform adjustments occur frequently and present ongoing management challenges;
2) the region is large enough to characterise the variability in channel stream order; and assess planform adjustment and stability at the reach, catchment and multiple catchment scale, and;
3) the region has available topographic, historic maps and air photographs and flow data that can be used to identify historic patterns of adjustment and endogenic and exogenic forcing.

The chapter concludes by outlining the reach, catchment and multiple catchments used in this thesis, which constitute the focus of Chapters 4, 5 and 6.

3.2 The Lake District upland region

The Lake District upland region (Fig. 3.1), covers an area of 2300 km^2. The region has a dome like topography with the highest mountain summits in England (Scafell Pike (978 m), Scafell (964 m), Helvellyn (950 m) and Skiddaw (931 m)), which are separated by a radial pattern of lower elevation valleys, many containing lakes (Fig. 3.1). Lake Windermere has the largest area (14.76 km^2) and the deepest lake is Wast Water (maximum depth 76 m) (Fryer, 1991). The region is within England's largest National Park, an area popular for tourism and recreation, which was named as a UNESCO World Heritage Site in 2017. The geomorphology of the Lake District is strongly influenced by the regional geology, glacial legacy, prevailing climate and anthropogenic activity which influences the spatial and temporal pattern of river planform adjustment and stability.

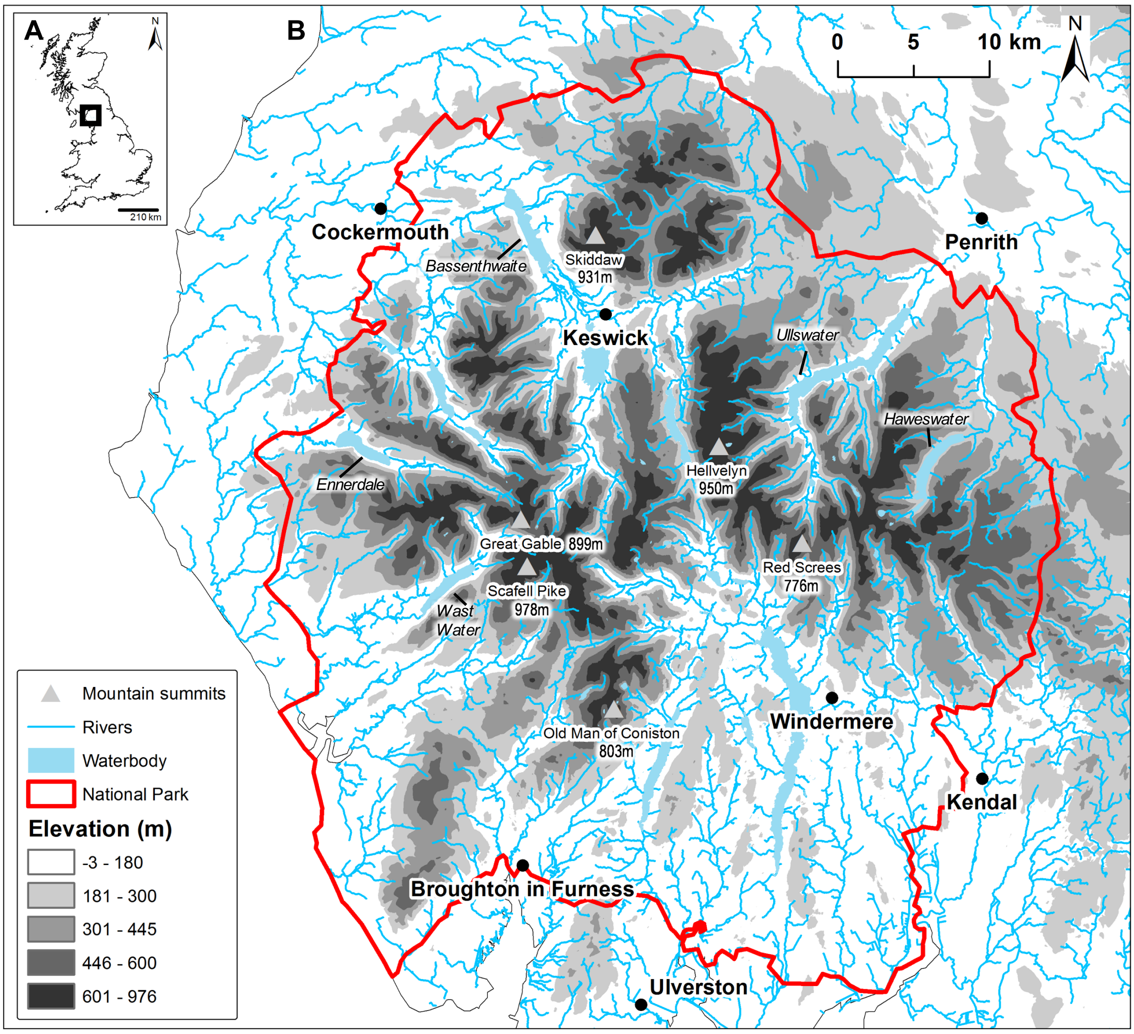


Figure 3.1. (A) The Lake District upland region located north-west England, and (B) elevation range, mountain summits and Lake District National Park boundary.

3.3 Regional geology

The geology of the Lake District originates from volcanic activity of the Ordovician and Devonian periods over 500 Ma (Figs. 3.2, 3.3) (Stone et al., 2010; Wilson, 2010). Three major bedrock zones exist across the region and include: the Skiddaw Group, the Borrowdale Volcanic Group and the Windermere Supergroup (Fig. 3.4), which determine surface erosional processes and landscape evolution (Smith, 2019).

The Skiddaw group lies in the north of the Lake District and covers an area of *c.* 500 km^2 with smaller inliers in the southern and eastern Lake District (Stone et al., 1999). The Skiddaw Group is the oldest group of rocks in the region formed during the Cambrian (Fortey et al., 1993) and Ordovician periods (444 – 488 Ma) (Fig. 3.3) (Stone et al., 1999). The Skiddaw group is a *c.* 5 km thick sequence of deep water marine turbidites that have been deformed and metamorphosed into Skiddaw slates, mudstones, siltstones and sandstones (Cooper et al., 1995; Evans and McDougall, 2015). The rocks are prone to fracturing into small slaty segments and mountains in this area have smooth slopes (Smith, 2019).

The Borrowdale Volcanic Group occupies an area of *c.* 800 km^2 across the central belt of the Lake District (Fig. 3.2). This group is characterised by lava piles (andesites), pyroclastic rocks, tuffs and agglomerates that were created by the collapse of a volcanic island arc and development of complex calderas in the late Ordovician period (Stone et al., 2010; Evans and McDougall, 2015). The Borrowdale Volcanic Group underlie the highest parts of the central Lake District and include the mountain summits of Scafell Pike, Scafell, Helvellyn, Old Man of Coniston and the Langdale Pikes. The Borrowdale Volcanic sequence is stratigraphically complex due to different patterns of volcanism (Stone et al., 2010), and can be divided into 'lower' and 'upper' parts based on contrasting eruptive phases (Fig. 3.2). An early eruptive phase is associated with andesite lavas (Eycott Volcanic Group) and a later silicic phase is associated with explosive activity and eruptions of pyroclastic density currents resulting in caldera formation (Moseley, 1978; Stone et al., 2010), (Fig. 3.2). Therefore, the upper part of the Borrowdale Volcanic Group comprises of large volume acidic ignimbrites and tuffs with extensive accumulations of volcanoclastic sedimentary rocks *c.* 3.2 km thick (Petterson et al., 1992). The lower part, *c.* 2.7 km thick, is composed of andesite lava flows with basalts, dacites and subordinate intercalations of colonic material (Petterson et al., 1992). As a result, these rocks create a resistant rugged terrain with widespread cliffed and stepped bedrock outcrops (Smith, 2019; Evans and McDougall, 2015).

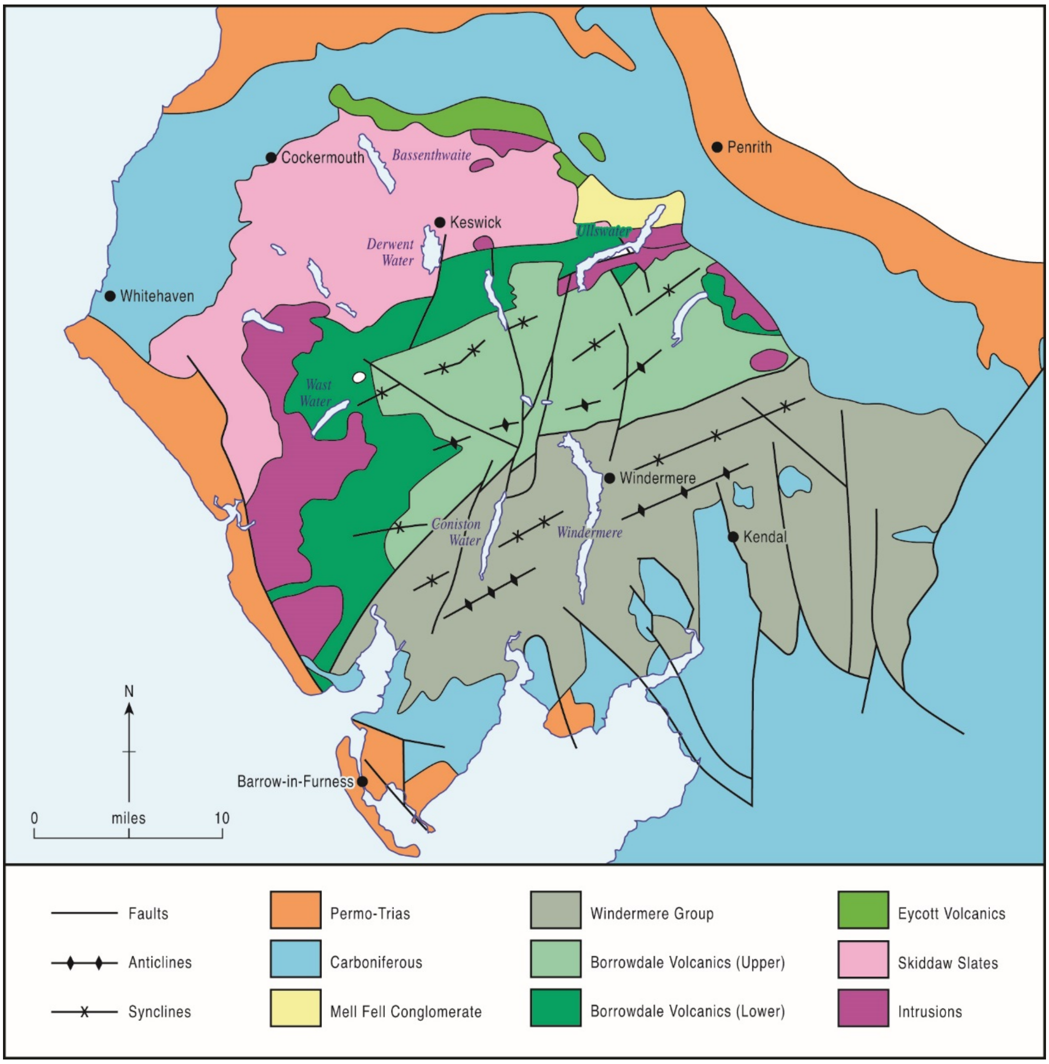


Figure 3.2. Generalised geology map of the Lake District showing the main bedrock geology groups (modified from Wilson, 2010).

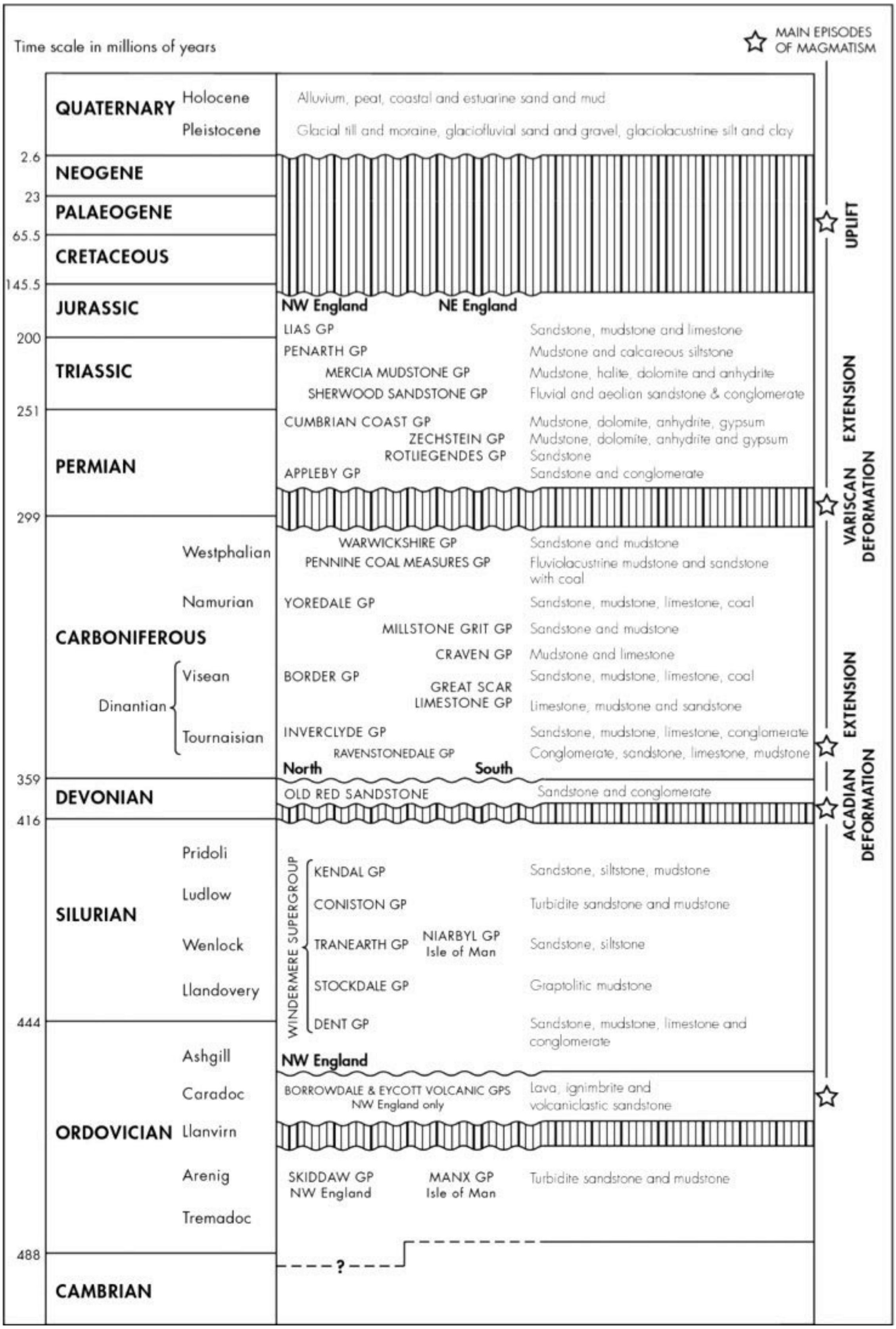


Figure 3.3. Geological succession for northern England from Stone et al., (2010), vertically hatched areas and stars show the main episodes of magmatism.

The Windermere Supergroup outcrop covers an area *c.* 1000 km^2 in the southern Lake District and comprises late Ordovician and Silurian age marine deposits of limestones, mudstones, siltstones, gritstones and sandstones modified by low grade metamorphism (Millward et al., 2000; Evans and McDougall, 2015). The Late Ordovician succession forms the Dent group inliers. Silurian succession forms the Stockdale, Tranearth, Coniston and Kendal groups. The Windermere Supergroup is *c.* 1.5 - 2 km thick (Stone et al., 2010). The different resistance of the limestones, sandstones and gritstones give rise to a scarp and vale topography in the Windermere Supergroup region (Smith, 2019).

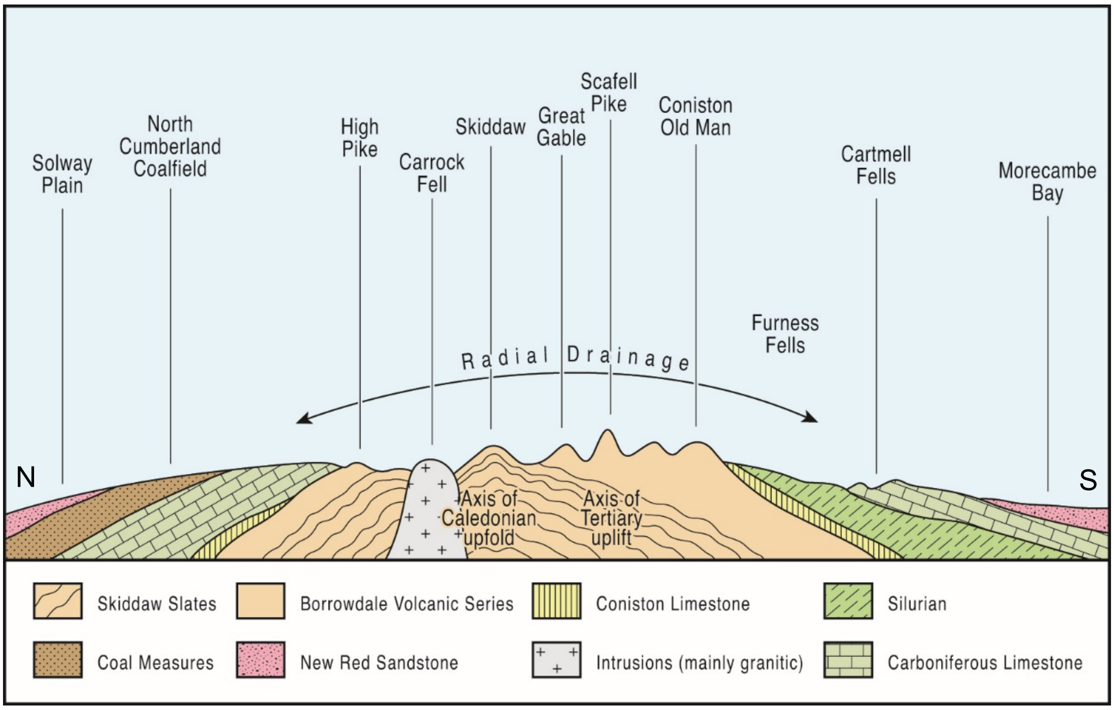


Figure 3.4. Geological cross section from North to South through the Lake District upland region showing the up doming through the central Lake District, and generalised pattern of radial drainage (source: Monkhouse, 1960).

The three bedrock zones have been modified by igneous activity. On the western side of the Lake District Ordovician and lower Devonian granitic intrusions have emplaced the Skiddaw and Borrowdale Volcanic groups (Fig. 3.2) (Evans and McDougall, 2015). Examples of these granitic intrusions include the Wasdale batholith, and the Eskadale Granite Pluton. Concealed intrusions underlay areas of the Borrowdale Volcanic group and parts of the Skiddaw group, intrusions include the Dunmail and Rydal Ordovician felsic intrusions. The Carrock Fell uplifted centre represents Ordovician mafic intrusion into the Skiddaw Group (Fig. 3.4) (Stephenson et al., 2000). Anticlines and synclines are east-west trending (Fig. 3.2) and are disrupted by south-west to north-east trending faults (Boardman, 1988).

The geological history influences the drainage pattern of the Lake District. Wordsworth (1835) described the drainage pattern of the Lake District as *"diverging...like spokes from the nave of a wheel"* where river channels radiate from high relief areas around Great Gable and Scafell downwards (Fig. 3.4). Mill (1895) similarly described the drainage pattern radially, as a series of concentric circles from a midway point between Stake Pass and Dunmail Raise on the western slope of High Raise (762 m NGR NY 283 096) (Fig. 3.5). The circle of 10 km radius is the commencement of the lake radiating system, touching the north of Windermere and the south end of Derwent water (Fig. 3.5). A radius of 15 km characterises central Lake District, passing through some of the deepest parts of Windermere of Ullswater and the northern end of Derwent water (Fig. 3.5). A 20 km radius passes through the lower end of Coniston Water, Windermere, the middle of Haweswater and lower end of Ullswater, the upper end of Bassenthwaite and middle of Ennerdale (Fig. 3.5). In contrast, Marr (1916) described the drainage system like that of an up-turned caddy spoon (Fig. 3.6), where rivers drain radially the inverted 'bowl' of the spoon (near Scafell Pike) and the drainage pattern from the handle would be oblique (west-east aligned of the Helvellyn range).

However, the simple interpretation of the radial drainage pattern is complicated by local structural controls (Boardman, 1988; Wilson, 2010), (Fig. 3.2). For example, the Coniston fault creates the valleys from north of Coniston water, Dunmail Raise, Thirlmere and St John's in the Vale to Threlkeld (Boardman, 1988; Wilson, 2010), (Fig. 3.2). The drainage pattern has further evolved due to quaternary glaciation (Wilson, 2010; Evans and McDougall, 2015).

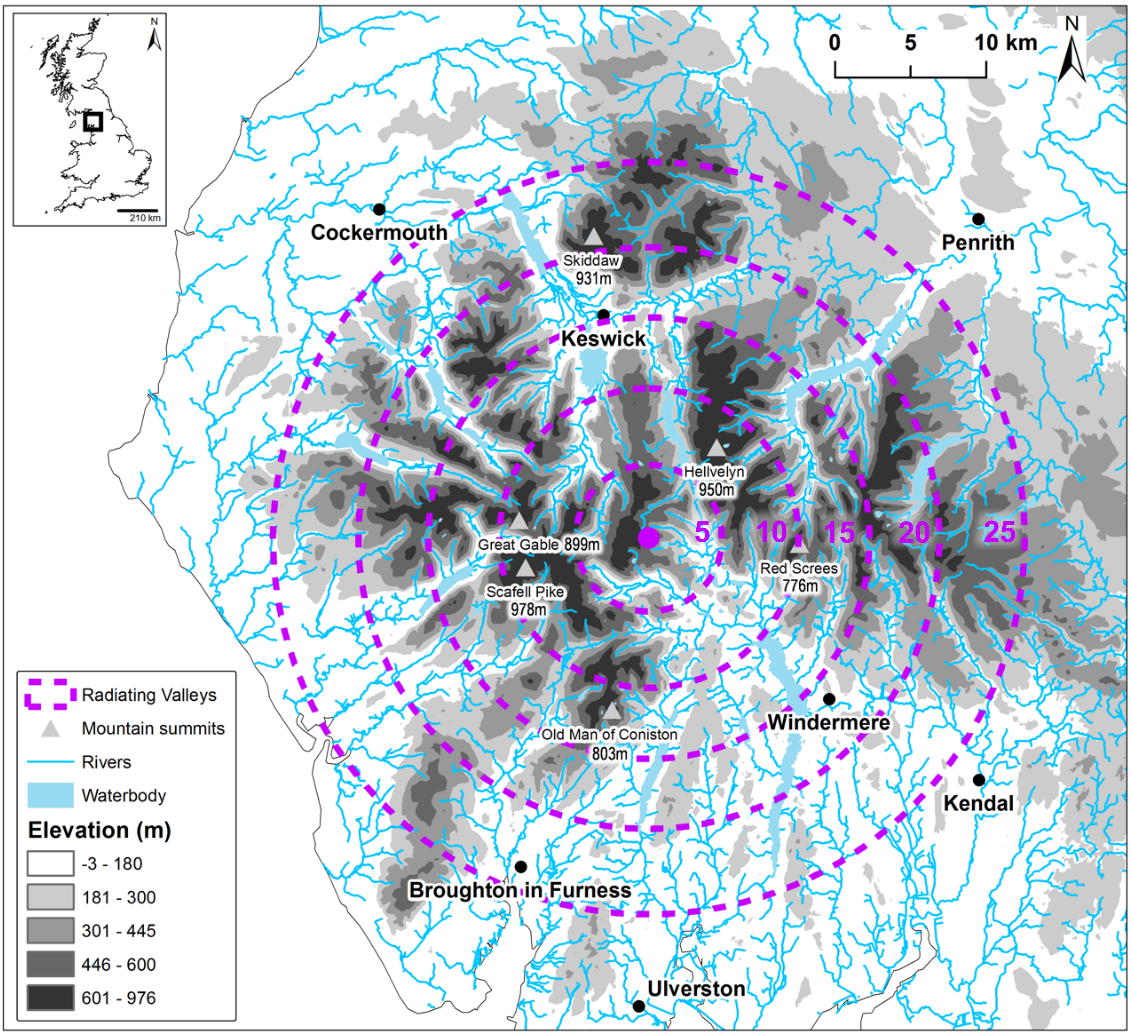


Figure 3.5. Radial symmetry of the Lake District after Mill (1895) shown by concentric circles (km).

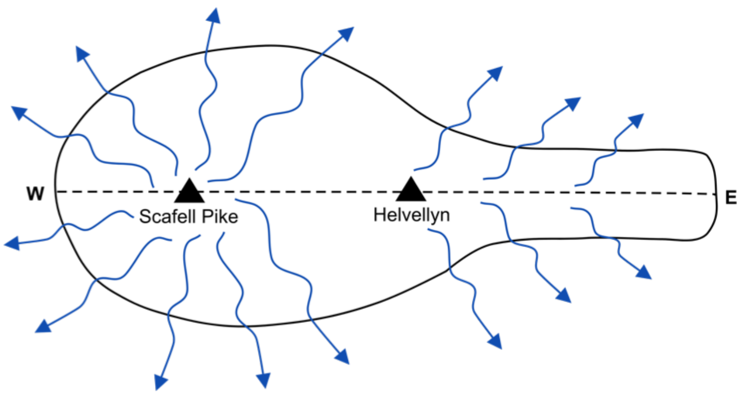


Figure 3.6. Conceptual diagram of the Lake District drainage pattern (blue arrows indicate flow direction) after Marr's (1916) upturned "caddy spoon".

3.4 Quaternary glaciation

The topography and drainage pattern of the Lake District has further evolved and been modified during Quaternary glaciations, creating U-shaped valleys and over-depended glacial troughs (Wilson, 2010; Evans and McDougall, 2015), of which many are now lakes (Table 3.1). Lakes are an important feature in the upland sediment cascade acting as long term sediment sinks capturing the upstream sediment supply, therefore influencing sediment continuity (Rapp, 1960; Dietrich and Dunne, 1978). Table 3.1 documents the largest lakes in the Lake District upland region, it is important to understand the location of these lakes as they are likely to influence the transfer of bedload sediment, and therefore planform adjustment patterns.

Table 3.1. Area, mean depth and maximum depth of the largest lakes in the Lake District upland region after Fryer (1991). Catchment area (km^2) represents contributing area upstream of the lake outlet.

Lake	Area (km^2) Lake	Area (km^2) Catchment	Mean Depth (m)	Max Depth (m)
Windermere	14.8	240	21.3	64
Ullswater	8.9	147	25.3	62.5
Derwentwater	5.4	80	5.5	22
Bassenthwaite Lake	5.1	360	5.3	19
Coniston Water	4.9	63	24.1	56.1
Haweswater*	3.9	32.5	23.4	57
Thirlmere*	3.3	53.4	16.1	46
Ennerdale Water*	3	44	17.8	42
Wast Water*	2.9	45	39.7	76
Crummock Water*	2.5	62.5	26.7	43.9
Esthwaite Water	1	16.6	6.4	15.5
Buttermere	0.94	16.8	16.6	28.6
Grasmere	0.64	28.6	7.7	21.5
Loweswater	0.64	7.8	8.4	16

** indicates lakes with water abstraction and downstream flow regulation*

The Dimlington Stadial (115,000 – 11,700 yr BP) ice sheet of the Late Devensian covered the Lake District upland region, with ice sheet flow paths following the radial drainage pattern (Wilson, 2010), (Fig. 3.7). Deglaciation following the peak of the Dimlington

Stadial at *c.* 22 ka BP (Boulton et al., 1977) resulted in widespread deposition of glaciofluvial sediment (sand and gravels) which formed kames, eskers, proglacial sandur, deltaic sands and gravels which determine the floodplains, sediment calibre and source in the rivers network (Busby and Merritt, 1999; Brown, 2009).

A second 'land-glaciation' (Ward, 1873; 1875) affected the higher valleys in the Lake District (e.g. around Scafell) during the Loch Lomond Stadial *c.* 12.9 and 11.7 ka BP where there was a renewed cooling that was associated with the regrowth of smaller glaciers around Scafell Pike, Helvellyn, contributing to further enhanced erosion of the drainage network and reworking of glacial sediments (Marr, 1916; Sissons, 1980; Bickerdike et al., 2016). These glacial sediments create the sediment supply for the rivers. The Lake District geological and glacial legacy has therefore influenced the topography drainage pattern, sediment calibre and supply to river channels. This legacy influences the present-day patterns of sediment continuity and planform adjustment (Wilson, 2010).

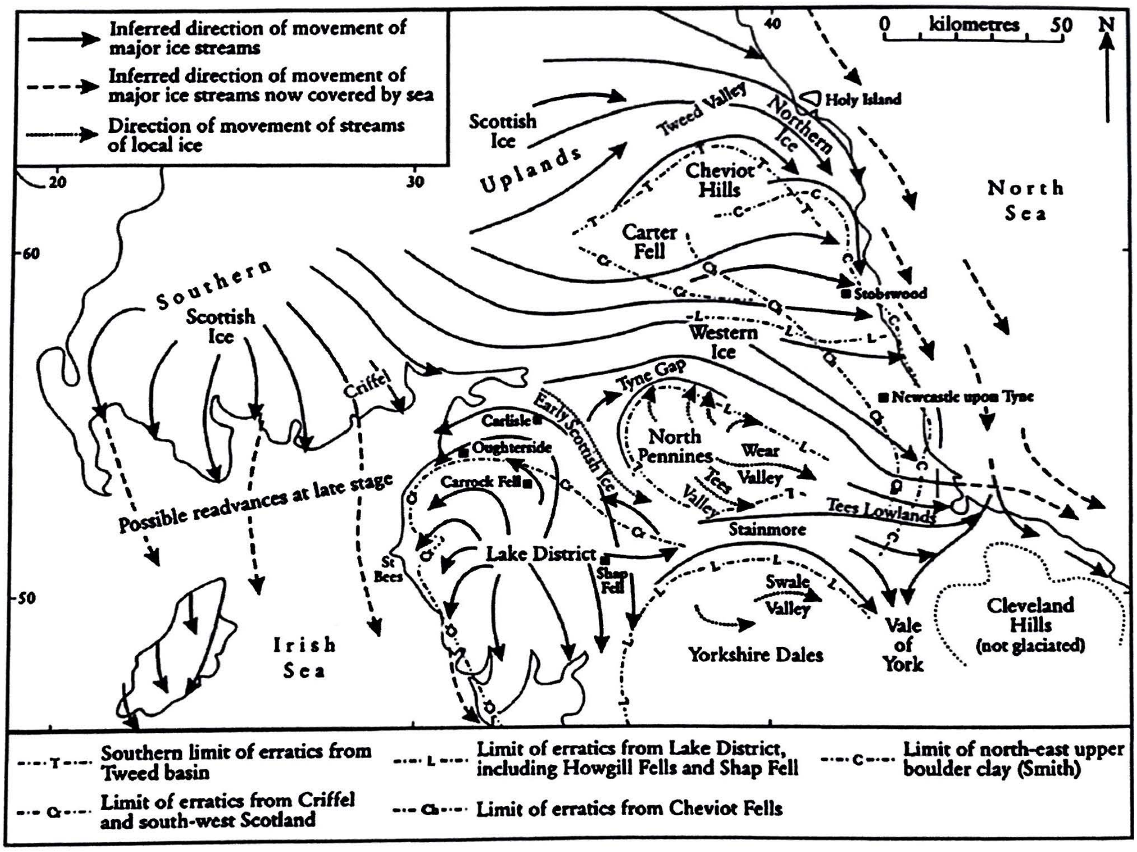


Figure 3.7. Generalised radial ice flow directions during the Dimilingtion Stadial across the UK (source: Taylor et al., 1971).

3.5 Landscape evolution during the Holocene

The geological and glacial legacies set the topographic conditions (i.e. confinement, U-shaped valleys, valley size) and the calibre and supply of sediment to rivers within which river systems operate during the Holocene (Macklin, 1999). Following glaciation Lake District rivers underwent progressive valley-floor incision in response to a decline in sediment supply (due to the melting of glaciers), and glacio-isostatic uplift (Macklin, 1999). The coarse sediments that were supplied to the rivers during glaciation are stored in the channel bed, banks and on floodplains and are only intermittently transported and reworked in rivers during high flow events and therefore remain stored within the system (McEwen and Werritty, 1988). The present day superficial geology of the Lake District reflects the glacial legacy and consists of: 63 % glacial deposits, 10 % fluvial deposits, 10 % organic deposits, 7 % mass movements, 2 % glaciofluvial deposits, 3 % marine and coastal deposits (British Geological Survey, 2016), (Fig. 3.8). The superficial geologies are not evenly distributed across the Lake District National Park (Fig. 3.8) and therefore the impact of superficial geology on river planform adjustment and stability will be spatially variable.

During the early Holocene, as temperatures rose following the Loch Lomond Glaciation, woodlands colonised much of the Lake District region up to an altitude of *c.* 550 m (Pennington, 1964; Pennington, 1965). Changes to the land use and subsequently forest cover over the Holocene have caused changes in sediment supply and transfer through the upland sediment cascade from hillslopes to rivers and then into long term lake sinks (Mackereth, 1966; Pennington, 1991; Edwards and Whittington, 2001; Chiverrell, 2006). Sediment cores from lakes have been used to document landscape instability in response to changes in climate change and anthropogenic activity during the Holocene (Mackereth, 1971; Chiverrell, 2006; Chiverrell et al., 2019). There has been an increase in sedimentation during the Holocene observed in multiple lakes across the Lake District upland region (Table 3.2), this corresponds to a decrease in forest cover identified in pollen records (Hatfield and Maher, 2009b), (Fig. 3.9). Hence, increases in sedimentation rates correspond with major forest clearances and changes in anthropogenic activity during Neolithic, Iron Age and Romano-British, and medieval times (Edwards and Whittington, 2001; Chiverrell, 2006; LDNPA, 2017; (Table 3.3)). Following the establishment of the Forestry Commission *c.* 1919 several Lakeland valleys were reforested (e.g. Ennerdale, Thirlmere); however, these catchments are carefully managed to prevent wood from entering low order tributaries. Therefore, due to historic forest clearance and management of several reforested catchments in the Lake District uplands, the occurrence of large wood or log jams in upland rivers is unlikely, and therefore will not be a dominant driver of reach scale planform adjustment over the period of measured change. Table 3.3 documents changes in land use practices over the Holocene in the Lake District (LDNPA, 2017). It is important to understand that in the study region there has been a long-term legacy of anthropogenic activity which has potential to influence historic river sediment supply and planform stability. Whilst many of the anthropogenic activities documented in Table 3.3 may have now ceased, it is possible that channels may still be responding to the changes in flow regime or sediment supply over the era of measurable change (Wohl, 2015).

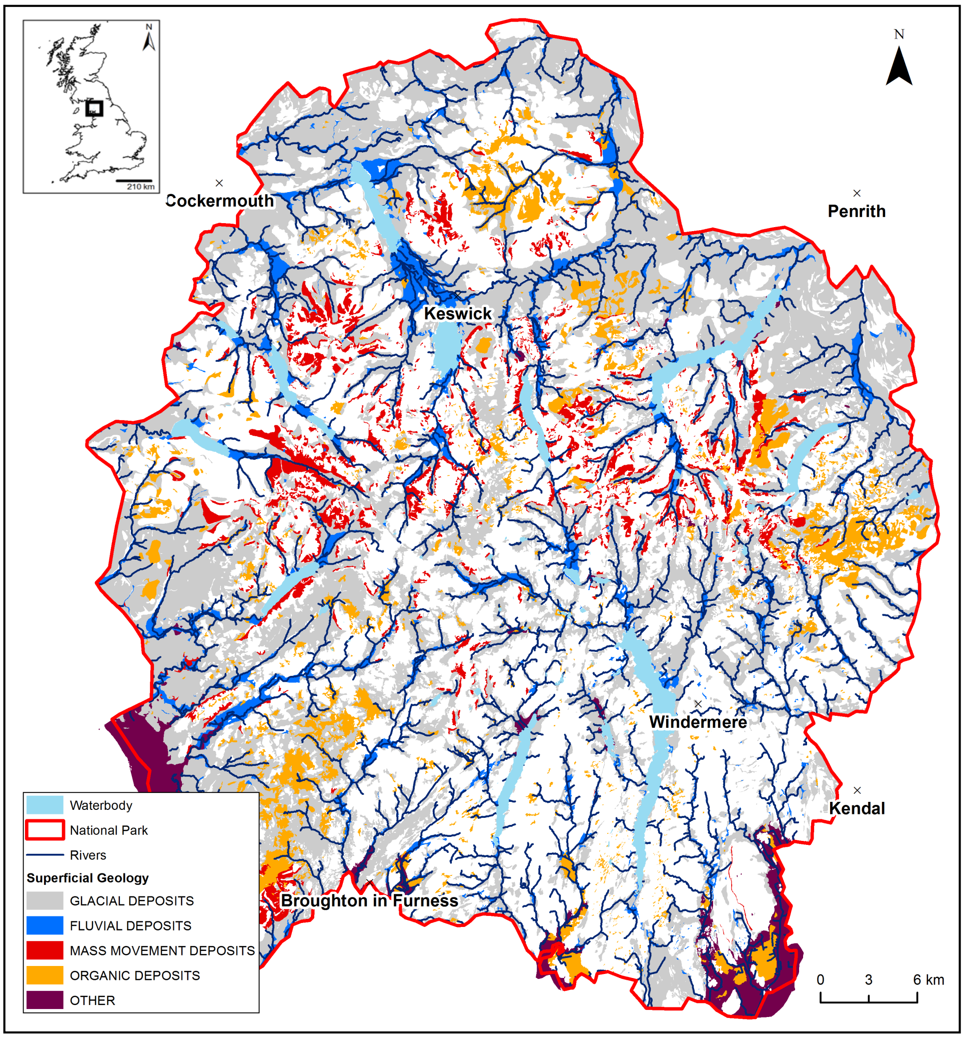


Figure. 3.8. Superficial geology in the Lake District National Park. White areas indicate bedrock outcrops, other superficial geologies include: aeolian, lacustrine, marine and coastal deposits and residual deposits (Source: British Geological Survey, 2016).

However, the pattern of Holocene sedimentation is not consistent across the entire Lake District upland region and there is local variability in sedimentation rates recorded in lake sediment cores due to differences in catchment characteristics and spatial variability in anthropogenic activity (Table 3.2). For example, larger lakes (e.g. Windermere, Table 3.2) are often buffered by smaller lakes higher within the catchment (e.g. Grasmere and Rydal Water) that retain a considerable proportion of the sediment flux, therefore accumulation rates are not as rapid (Chiverrell, 2006). Early Holocene populations may have exploited lake edges and lowland areas with well drained soils (Chiverrell, 2006) for agriculture contributing to elevated levels of sedimentation. Changes in land use in the late Holocene and the introduction of hill farming may have had a more widespread impact (e.g. increase in peat and soil erosion) on sediment supply to upland rivers (Chiverrell, 2006). Therefore, river planform adjustments over the last *c.* 150 years may reflect the impact of past anthropogenic activities on the supply of sediment to rivers.

Table 3.2. Sediment accumulation rates, in mm year^{-1} during the Holocene in Lake District lakes (source: Chiverrell, 2006). Chronology information derived from Mackereth (1971), Turner and Thompson (1981), Pennington (1964; 1981; 1991) and Harkness et al. (1997).

Lakes	**Early Holocene** 5000-9000 years BP	**Mid - late Holocene** 0-5000 years	**Late Holocene** 0-2500 years	0-1000 years
Windermere	0.2	0.5	0.6	0.6
Coniston Water	0.1	0.6	1.2	1.3
Ennerdale	0.6	0.7	0.6	1
Crummock Water	0.4	0.5	0.6	0.6
Ullswater	0.3	0.6	0.7	0.7
Esthwaite	0.2	0.7	0.8	1
Burnmoor Tarn	0.4	0.6	-	0.7
Red Tarn (Langdale)	0.6	0.3	-	0.9
Seathwaite Tarn	0.8	0.8	0.9	1.2
Brotherswater	-	-	2	2

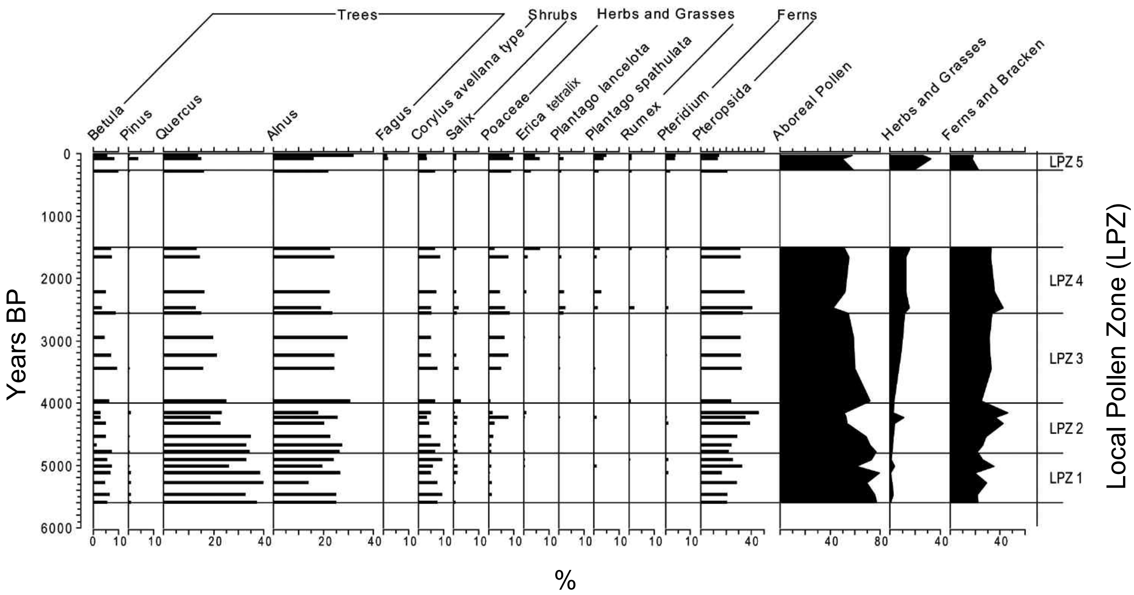


Figure 3.9. Percentage pollen diagram for selected taxa in Bassenthwaite Lake cores over the last 6000 years BP (source: Hatfield and Maher, 2009b).

Table 3.3. History of Holocene land use change in the Lake District upland region (modified from: LDNPA (2017)).

Time Period	Land use / cover
Palaeolithic *c. 12,000 BC* *c. 8,000 BC*	• Small groups of hunter/gatherers.
Mesolithic *c. 8,000 BC* *– 4,000 BC*	• Larger groups of hunter/ gatherers concentrated on coast. • Most of Lake District covered by forest by 4,000 BC. Max extent of forest *c.* 5,000 BC. • Microlithic flint industry (very small flints used to make composite tools).
Neolithic *4,000 BC –* *2,000 BC*	• First evidence for agriculture but settlement still mobile, and hunting and gathering still important for subsistence. • Small temporary clearances in woodland.
Bronze Age *2,000 BC –* *800 BC*	• Warmer climate allowed settlement on higher ground up to c. 300 m. • Small, temporary clearances in forest cover in early Bronze Age and more permanent clearance by Late Bronze Age. • Introduction of copper and then bronze technology. Flint still in use.
Iron Age *800 BC –* *100 AD*	• Landscape now more open and probably highly organised, including woodland management; agricultural settlements in valleys and lower fells. • Introduction of iron technology.

Table 3.3. continued.

Romano British *100 AD – 400*	• Roman Forts established by *c.* 150 AD. • Road system established. • Mining of metal ores
Early Medieval *400 – 1092*	• Major woodland clearance episodes • Arable / pasture farming
Medieval *1092 – 1600*	• The Lake District was divided up by Norman aristocracy (1092). Large tracts of land later given to monasteries • Development of wool trade and iron industry. • Open field system with strip fields in valleys, enclosed by wall known as 'Ring Garth'. • More nucleation of village settlement and development of market towns (e.g. Kendal, Keswick, Ambleside). • Development of mining for copper, lead and iron.
Post Medieval *1600 – present*	• Breakdown of monastic ownership following dissolution. • Ownership of farms by individuals – gradual disappearance of open field system. Intaking onto fellsides and enclosure with more stone walls. Farming mainly pastoral with some arable. • Development of major industries – mining and quarrying; gunpowder; bobbin production; tanning; iron smelting; water industry. • Evolution of modern settlement pattern and transport (road then rail). • Extraction of water from lakes • Closure of mines • National Park Designation 1951 • Tourism • UNESCO World Heritage site designation 2017

3.5.1 Anthropogenic activity

Anthropogenic activity has both direct and indirect impacts on sediment continuity and river channel planform (Sear et al., 2000; Downs and Gregory, 2004; James and Marcus, 2006; Macklin and Lewin, 2008; Macklin et al., 2014; Gregory, 2019). This section discusses river channel management, land use and flow regulation in the Lake District over the last 150 years.

3.5.1.1 River management and maintenance

River channels have been directly modified since the Medieval period to protect land, homes and infrastructure from flooding across the Lake District region (Wilson, 2010). In the Lake District, channel modifications have included channelization, bank reinforcement, sediment dredging, vegetation management and flow regulation (Cumberland River Board Authority, 1950s – 1970s; Environment Agency, 2018). Several channelization schemes occurred prior to the first Ordnance Survey maps in the early 19th Century and therefore it is difficult to identify the timing of these works (Winterbottom, 2000). However, channelized rivers in the Lake District can be identified by straight uniform planforms and reinforced banks. Examples of these 'engineered' channels in the region include Newlands Beck, upstream of Bassenthwaite Lake (Fig. 3.10A), downstream of Thirlmere Reservoir on St John's Beck (Fig. 3.10B) and along the River Greta as it flows through Keswick (Fig. 3.10C).

The Cumberland River Board Authority reports provide a useful record of channel maintenance (i.e. dredging, bank repairs) on the main river channels from 1950 – 1970 in the Lake District. The management of rivers after this period was run by the Regional River Authorities and then National River Authorities (1989 – 1996), which has since has been superseded by the Environment Agency who currently manage and maintain these systems across catchment partnerships and with river trusts. Historically, river channel management has focused on hard engineering bank reinforcements or channel dredging (Cumberland River Board Reports 1950s-1970) on the lowland sections of rivers around settlements and farmland. However, more recently a move to natural based management and restoration of the biological and physical function of these rivers is being adopted (National Trust, 2019; South Cumbria Rivers Trust, 2019; West Cumbria Rivers Trust, 2019). For example, recently funded projects include the restoration and re-meandering of Goldrill Beck (upstream of Ullswater lake NGR NY 395 163), a previously straightened and reinforced channel (National Trust, 2019). An example of a recently completed restoration scheme in the upland study region is on Swindale Beck (NGR NY 511 128) in the north-east of the Lake District (Fig. 3.10D). The channel had been historically straightened and aligned with rock armour on the channel banks and levees, disconnecting the channel from the floodplain and restricting lateral adjustment. In 2016 890m of new/restored sinuous channel was created, replacing the 750 m length of straightened channel (RESTORE, 2016). The old channel was filled in and reseeded (RESTORE, 2016). These examples highlight the direct impact of anthropogenic activity on river planform. Future catchment re-wilding and the use of in-channel large wood and log jams for river restoration and natural flood management will potentially cause localised reach scale planform adjustment (Grabowski et al., 2019).

3.5.1.2 Industrial activity: mining, gravel extraction and woodland industries

Figure 3.11 summarises the spatial location of the key industries: mining and quarrying, water-power and woodland industries, within the Lake District upland region. Industrial activity increased in intensity and extent after *c.* 1600s (LDNPA, 2017). Therefore, these industries have potential to influence sediment continuity and planform adjustment over the period of measurable change.

The Lake District has a history of mining for lead, copper, graphite silver and slates due to the bedrock geologies (Figs. 3.2; 3.11). Mining activities influence sediment supply and regulate river discharge (Macklin, 1986; Higgitt et al., 2001; Warburton et al., 2002; Wishart, 2004). An enhanced supply of sediment from mining activities can enter the channel network which can lead to sediment aggradation and lateral instability or sediment can be transported downstream and deposited in lakes.

The imprint of mining activities is evidenced in historic records of channel planform adjustments and downstream in lakes (Anderton et al., 1998; Grayson and Plater, 2008; Schillereff et al., 2016; Miller et al., 2014). An example of mining impacts on sediment continuity and river planform are documented around Greenside lead mine (1825 – 1961) upstream of Ullswater Lake (NGR NY 358 179, Fig. 3.11). Mining waste tipped on upland channel slopes provides a direct source of sediment to the channel, and the construction of dams and leats to provide water power for the mine results in direct modification (e.g. straightening, or re-direction) to channel planform (Anderton et al., 1998).

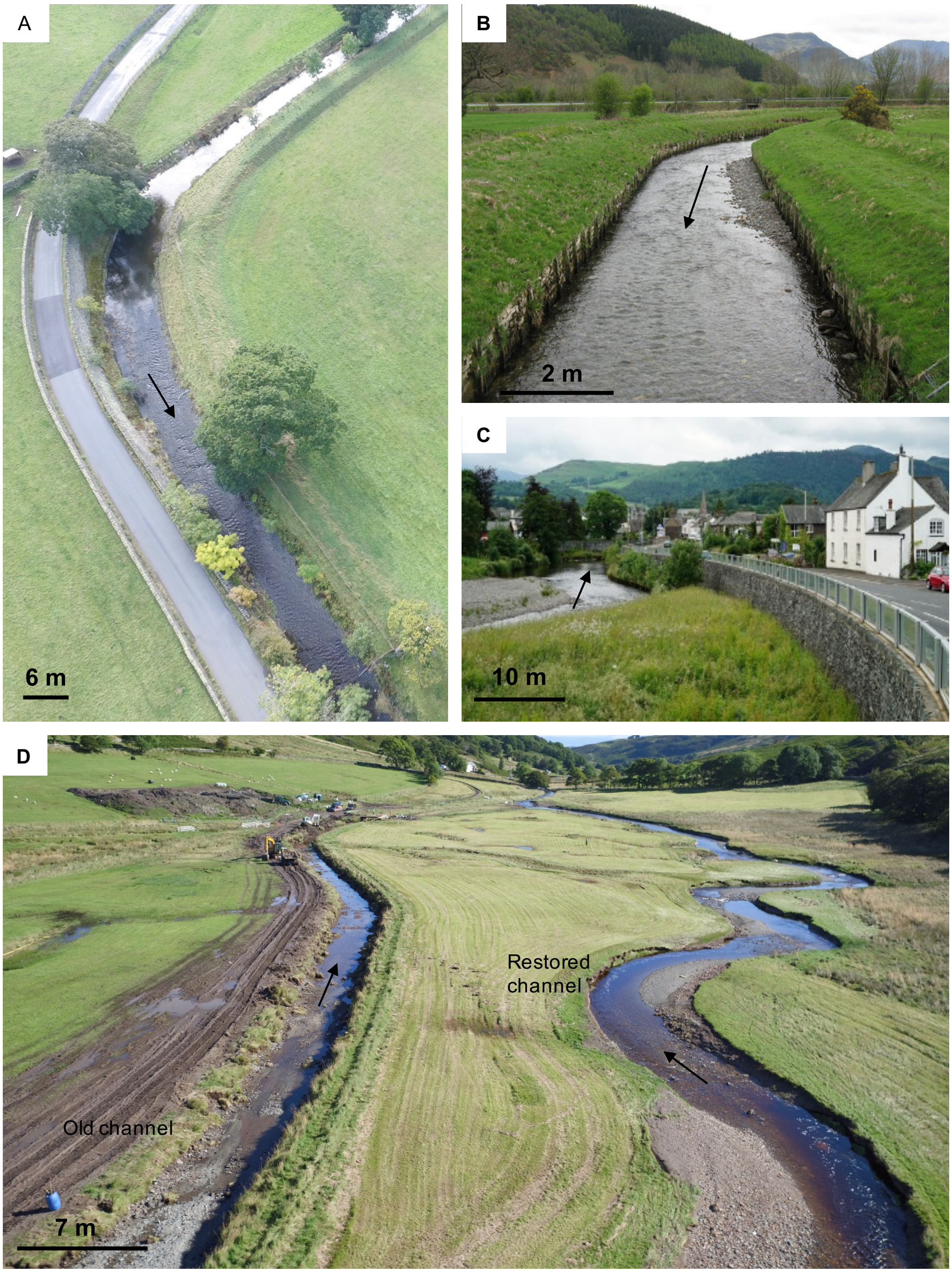


Figure 3.10. Examples of river management in the Lake District, arrows indicate flow direction. (A) Air photo of St John's Beck (NGR NY 317 213) showing straightened channel, with reinforced banks and embankments to protect road and agricultural land (2016). (B) Straightened and realigned Newlands Beck (NGR NY 240 236) with bank reinforcement and flood protection levees (source: Richardson, 2011). (C) River Greta flowing through Keswick with flood defence walls (Trimming, 2015). (D) Swindale Beck (NGR NY 511 128) river restoration scheme. Photograph shows comparative channel morphology of historically straightened (left) and restored (right) channel (source: RESTORE, 2016).

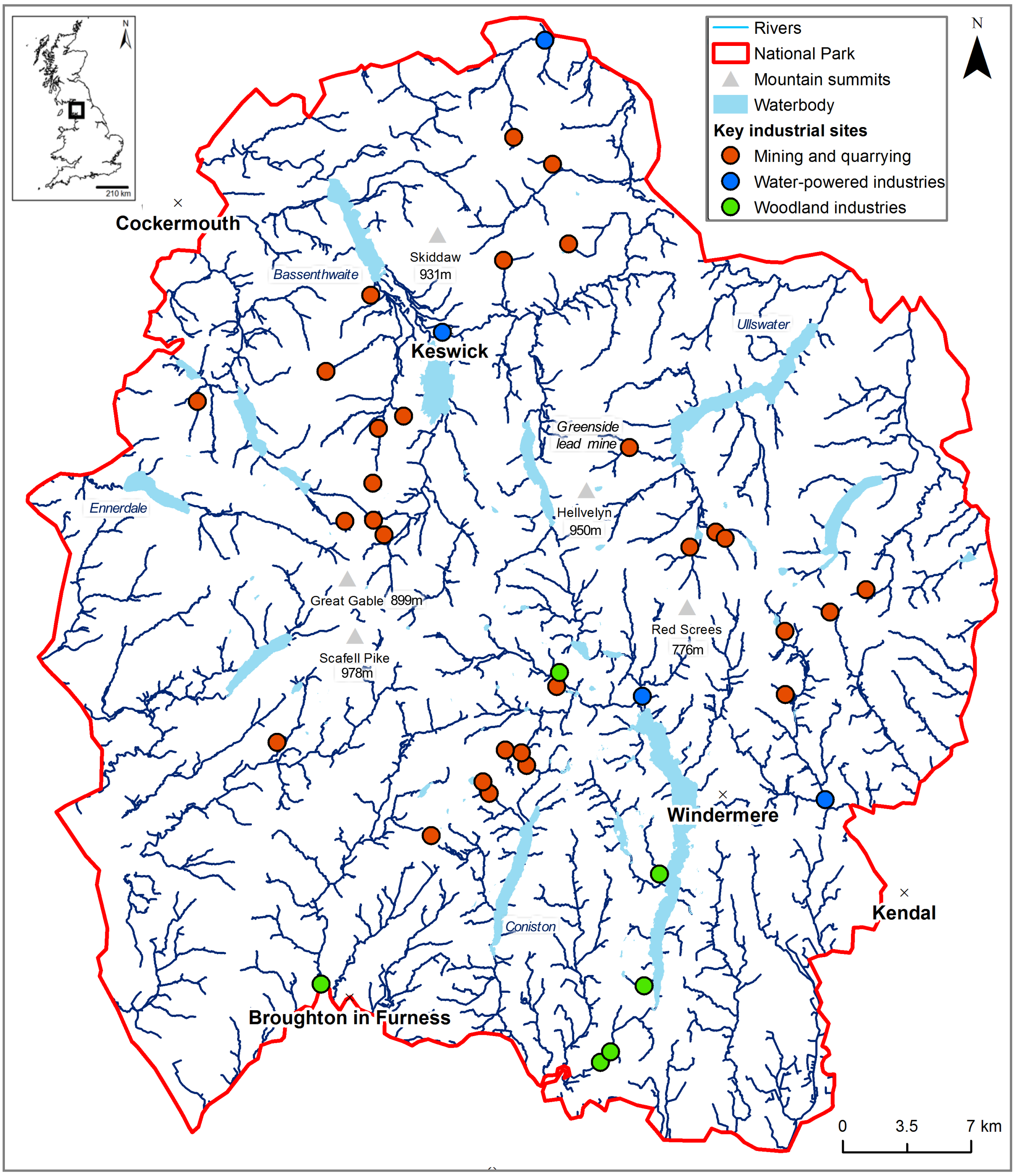


Figure 3.11. Key industrial sites, including mining and quarrying, water power and woodland industries in the Lake District National Park, modified from LDNPA (2017).

In addition to direct mining activities, dam failures at Greenside mine in 1877, 1927, 1931 instigated local changes to hydrology and sediment continuity and geomorphic work over the era of measurable change (Anderton et al., 1998). Of these dam failures, the 1927 Keppel Cove dam failure, triggered by intense rainfall event, caused significant geomorphic adjustment (Carling and Glaister, 1987; Anderton et al., 1998). Approximately, 1 m of sediment was scoured directly below the breached dam and further downstream sediment was deposited in fans and berms near Glenridding (Anderton et al., 1998). The stream bed was raised up to 1 m in the lower reaches by fine gravels and a considerable amount of sediment accumulated on the fan delta at the junction with Ullswater Lake (Carling and Glaister, 1987). This example demonstrates the spatial and temporal impacts mining activities can have on sediment continuity and planform adjustment across an upland catchment.

Channels in the Lake District upland region have also been modified for woodland and water-power industries (LDNPA, 2017), (Fig. 3.11). These industries include bloomer production of iron using water power at bloomer forges and for gunpowder production. The majority of mining and quarrying industries in the Lake District ceased by World War II due to foreign competition and more efficient production elsewhere in the UK (LDNPA, 2017). However, slate quarrying still occurs (Honister, Elterwater) but is at a smaller scale than in the past (LDNPA, 2017). Understanding the industrial history of the region is important as it can directly and indirectly influence flow and sediment continuity and therefore the potential for planform adjustment.

3.5.1.3 Lakes and reservoirs (flow regulation)

Glaciation in the Lake District created over-deepened basins which have formed lakes (Fig. 3.1). Lakes act as long term sinks of sediment disrupting sediment continuity from headwaters to lowland floodplain valley zones in the upland sediment cascade. In the Lake District, 6 of the principal lakes have been modified for water abstraction for drinking water or to support industry in the region, including: Thirlmere Reservoir, Haweswater Reservoir, Wet Sleddale Reservoir, Ennerdale, Wast Water and Crummock Water, Kentmere Reservoir (Table 3.1). As a result, these lakes have regulated flows downstream which can affect sediment transport capacity and potential for adjustment (Petts and Lewin, 1979; Gurnell, 1983; Williams and Wolman, 1984; Kondolf, 1997; Petts and Gurnell, 2005). For example, Thirlmere reservoir (NGR NY 311 167) was constructed by joining two smaller lakes and building a dam across a gorge and regulated flows downstream into St John's Beck. To ensure a continuous water supply to Thirlmere Reservoir, Raise Beck (NGR NY 330 118) was artificially diverted North (previously flowed South towards Grasmere) into Thirlmere Reservoir between 1920 and 1935 (Huddleston, 1935; Hindle, 1981). It is important to recognise that lakes are important features in USC, therefore it is expected that patterns of sediment continuity and planform adjustment will differ upstream and downstream of these features.

3.6 Climate

The Lake District has the highest annual rainfall totals in England (Met Office, 2017). Wordsworth (1895) wrote *"The rain comes down here heartily"*. Seathwaite, Borrowdale upstream of Derwent Water (NGR NY 233 119) is the wettest place in England receiving over 3400 mm year^{-1} of rain (Manley, 1946; Wilson, 2010), in contrast, Keswick receives 1500 mm year^{-1} (12 km north of Seathwaite), Kendal receives 1300 mm year^{-1} and Rosthwaite, upstream of Derwent water, receives 2550 mm year^{-1} (Tufnell, 1997; Wilson, 2010). The spatial heterogeneity in rainfall across the Lake District is related to orographic controls and rain shadow effects (Jones and Conway, 1997; Barker et al., 2004). Westerly air flows from the Atlantic are forced to rise over the mountain summits causing the moist warm air to cool, which then condenses resulting in the highest quantities of precipitation in the west and central Lake District (Mayes, 1996; Barker et al., 2004; Wilson; 2010), (Fig. 3.12).

Extreme rainfall and flood events in the Lake District region have been documented from archival sources dating to the 1690s and gauge data dating from 1860s to present (Watkins and Whyte, 2008; Met Office, 2017). The longest rainfall gauge in the Lake District dates back to 1866 at Helvellyn Birkside, (Fig. 3.13), (Met Office, 2017). Recent extreme rainfall and flood events include: the November 2009 flood, where 316 mm of rain fell in 24-hour period (480 year rainfall return period), and the extreme Storm Desmond flood event 4-6 December 2015 which broke the 24-hour rainfall total (Honister Pass 341.4 mm, 1300 year rainfall return interval) set by the 2009 flood. These recent floods are the largest in a flood series >558 years based on sediment stratigraphy in Bassenthwaite Lake cores (Chiverrell et al., 2019). The extreme rainfall events caused widespread flooding, channel adjustments and high sediment transport rates and disruption to infrastructure (Joyce et al., 2018). The estimated cost of damages resulting from the two floods is £276 million in 2009, and £1.6 billion in 2015, (Environment Agency, 2018).

Climate change is expected to increase the occurrence of extreme rainfall events similar to that of Storm Desmond and the 2009 event, as summers become warmer and dryer winter rainfall and extreme events are predicted to increase by approximately 15 - 30 % by 2080 (Cumbria County Council, 2008). Increases in extreme rainfall events will increase river discharge and affect the intensity and frequency of flood events and therefore the potential for sediment erosion and deposition and planform adjustment in the future (Coulthard and Macklin, 2001; Watts et al., 2015).

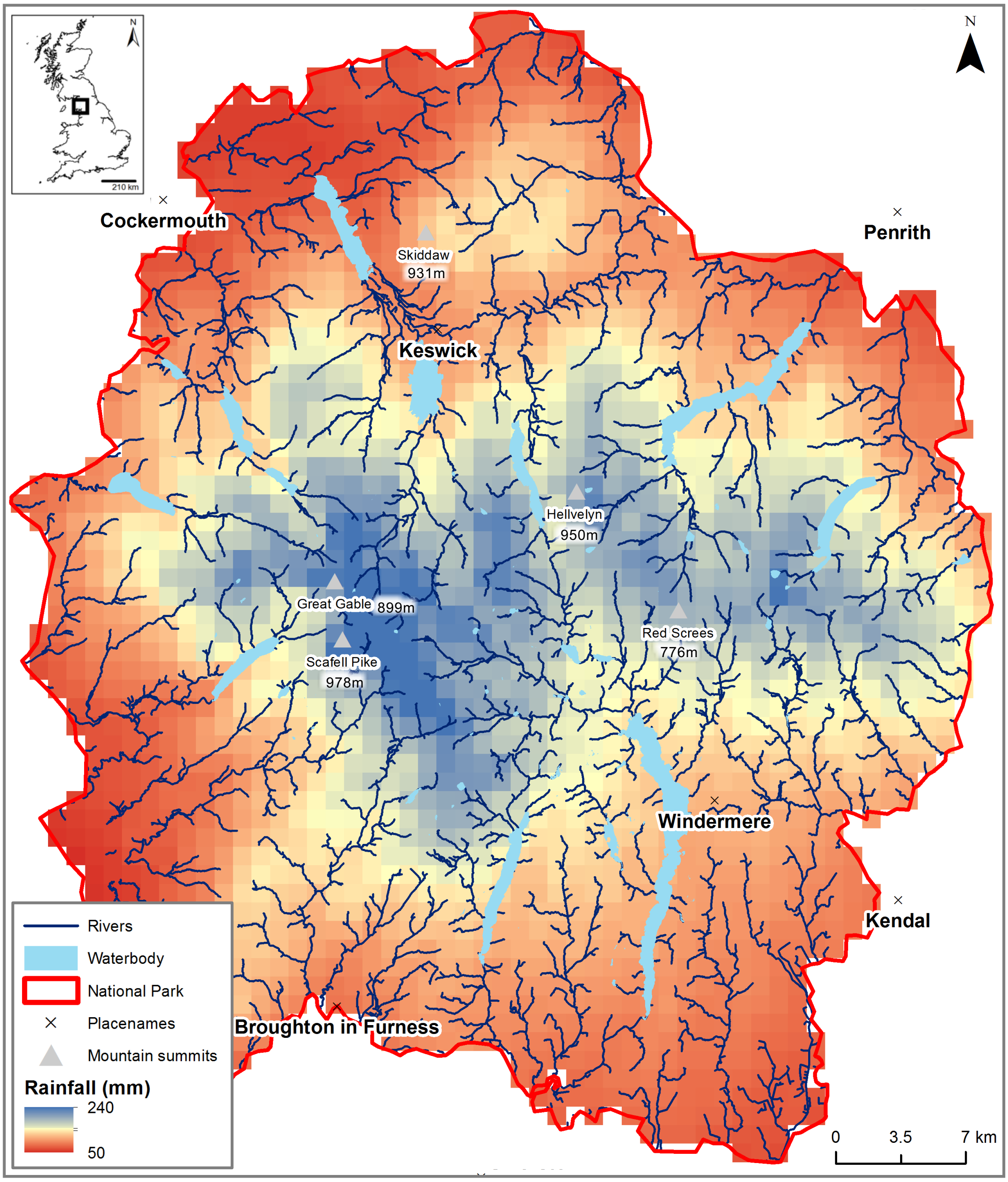


Figure. 3.12. Spatial distribution of mean monthly rainfall 1911 – 2010 in the Lake District upland region (source: Tanguy et al., 2019).

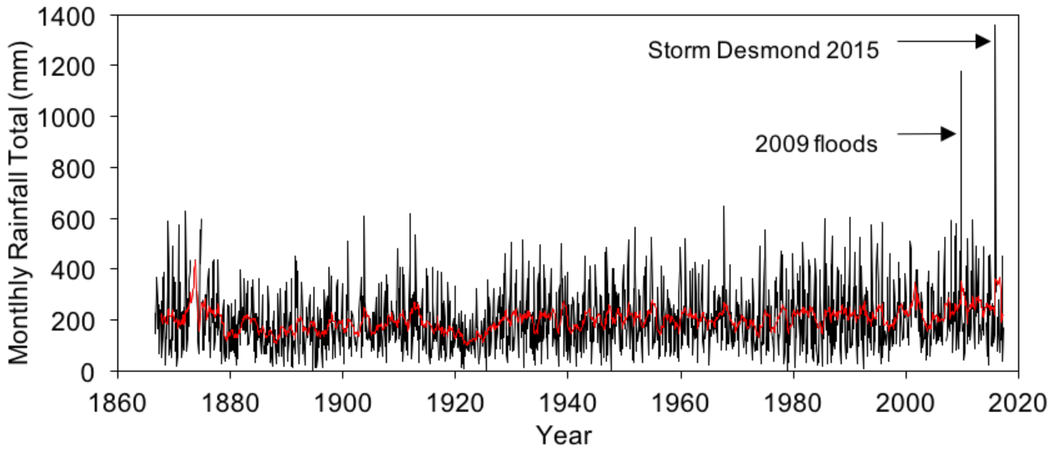


Figure 3.13. Long term (1866–2017) monthly rainfall (mm) variability from the Met Office Helvellyn Birkside rain gauge (NGR NY 338 133, elevation 655 m), red line indicates 12 month moving average.

3.7 Reach, catchment and multiple catchment scales of analysis

Previous research into river channel dynamics in the Lake District have been focused at the reach scale or on individual channels. These studies have included reconstructing and quantifying the impacts of flood events (Carling and Glaister, 1987; Carling, 1997; Johnson and Warburton, 2002; Joyce et al., 2018; Heritage et al., 2019; Heritage and Entwistle, 2019), sediment budgets (Johnson and Warburton, 2002b, 2006) investigating hillslope channel coupling (Johnson et al., 2008); estimating bedload sediment transport rates (Newson, 1985); modelling channel erosion during floods (Wong et al., 2015); river habitat surveys (Cooper, 2004); fluvial reconnaissance (Harvey, 1997); fluvial audit (Skinner and Haycock, 2004); and river energy audit (Soar et al., 2017). However, no previous studies have placed reach scale assessments of planform adjustment in the catchment or regional spatial context over the last 150 years in the Lake District.

This thesis quantifies the spatial patterns and geomorphic variables of upland river planform adjustment at the reach, catchment and multiple catchment scale over the last *c.* 150 years in the Lake District upland region. This section outlines the catchments studied in the Lake District. The downstream extent (end point) of the designated upland catchment is defined (1) at the end point of a waterbody (lake, reservoir or impoundment), or, where multiple waterbodies are present along the river network the end point is located at the outlet of the furthest downstream lake (if it lies within the upland region); and (2) if no waterbody is present the endpoint is located where the river channel network is no longer surrounded by hillslopes >300 m elevation (Atherden, 1992). Figure 3.14 displays the Lake District upland study area (1250 km^2), which occupies 55% of the National Park focusing on the upland catchments. In total, 17 catchments are studied in the upland region (size range 8 – 362 km^2), (Fig. 3.14).

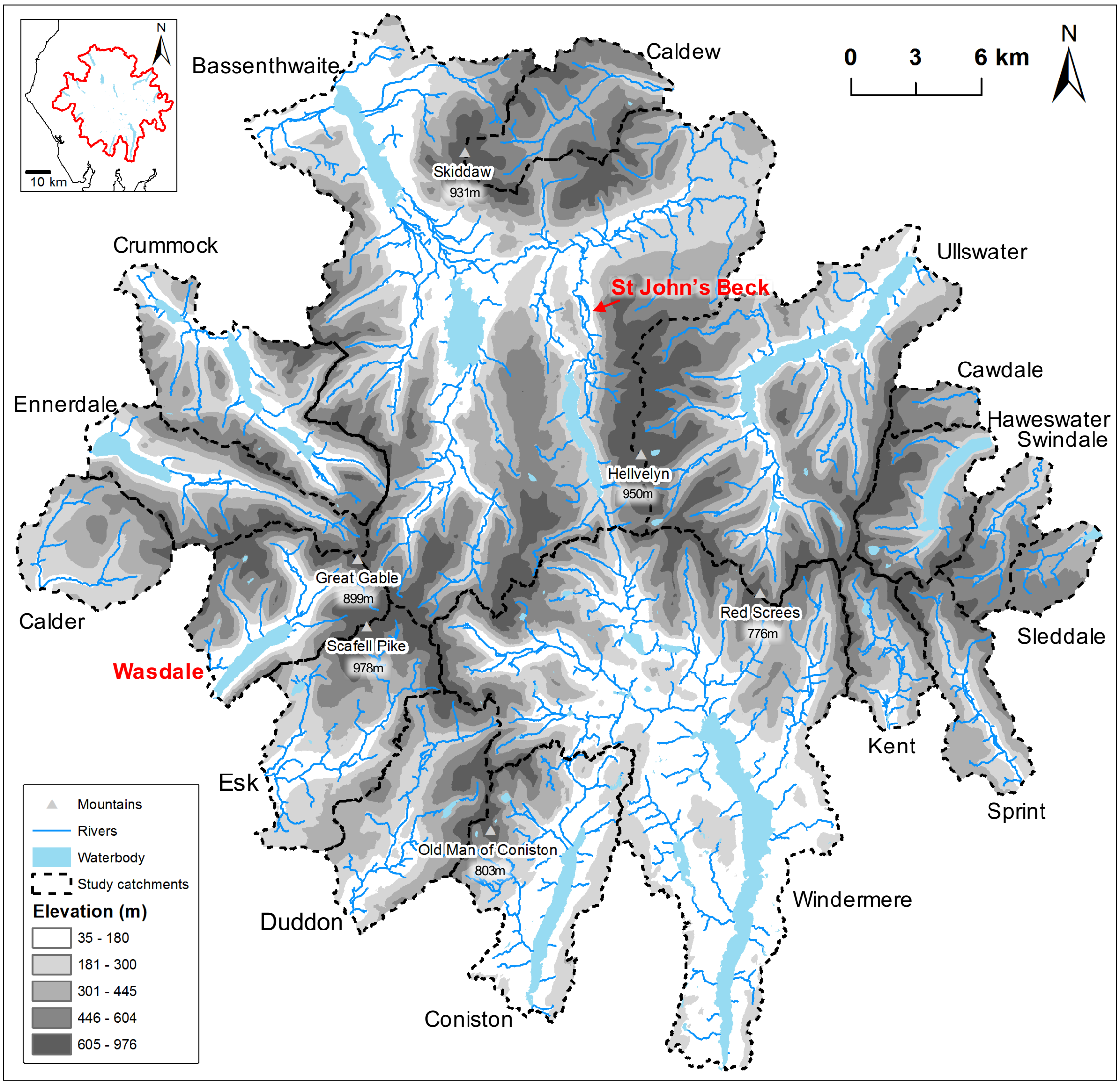


Figure 3.14. (A) Location of the Lake District upland study region in North-west England. (B) The 17 Lake District catchments studied within this thesis, which constitute the in the basis of Chapters 4, 5 and 6.

The research strategy adopted in this thesis takes a nested approach exploring patterns and controls of planform adjustment and stability at three different spatial scales: the reach, catchment and multiple catchment (region). At these spatial scales the pattern of river planform adjustment and stability is assessed during a flood event (Chapter 4) and over the past 150 years (Chapters 5 and 6).

Detailed reach scale field investigations (Chapter 4) were conducted on St John's Beck (Fig. 3.14) to explore short term channel planform adjustment and sediment dynamics in response to the extreme Storm Desmond, 2015 flood (Chapter 4). St John's Beck is a focus for the reach scale assessment as large quantities of sediment were eroded, transported and deposited during the December 2015 flood. St John's Beck was also easily accessible, had available historic sources of data, and had an upstream discharge and rainfall gauge. St John's Beck represents the floodplain valley transfer zone of the USC. The event scale patterns of sediment continuity and planform adjustment identified along St John's Beck are considered in the wider spatial and temporal context of sediment continuity and planform adjustment in Bassenthwaite catchment, and in the upland study region (Chapter 6).

At the catchment scale, a methodology is developed to assess patterns and controls of 2D planform adjustment and stability over the past *c.* 150 years (Chapter 5). The methodology is developed and initially tested in the Wasdale Catchment (Fig 3.14). The Wasdale catchment was chosen as it represents the production zone of the USC, it exhibits a rich variety of fluvial forms including: bedrock, confined, unconfined wandering and braided channels (Harvey, 1997), and has available historic data. The methodology developed in Chapter 5 is then applied to the remaining catchments in the study region to explore regional patterns and controls of planform adjustment and stability (Chapter 6). The scales of analysis allow local reach scale patterns of adjustment and stability to be considered in the wider catchment and regional spatial context at the event scale and over longer time scales of the past *c.* 150 years.

3.8 Data availability

In order to assess the spatial and temporal patterns and controls of planform adjustment and stability in the Lake District upland region it is important to collate available data for the region. Table 3.4 summarises the key data sources available for the Lake District that are used in this study. The following section describes the data sources and the information that can be derived from them.

A 5 m DTM (Edina Digimap, 2017) is used to provide topographic information (i.e. stream order, channel slope, catchment area). Environment Agency LIDAR data (1 and 2 m resolution) is available for the Lake District, however, the coverage is limited to valley bottoms and therefore does not characterise rivers from source to sink and therefore it is not used in this thesis.

Comparisons of historic maps and aerial photographs provide an indication of river channel planform adjustment over time (Lewin, 1987; Macklin and Lewin, 1989; Petts et al., 1989; Macklin et al., 1992; Downward et al., 1994; Milton et al., 1995; Winterbottom, 2000). The historic maps and air photographs used in this thesis are the Ordnance Survey county series maps 1867-68 (1:10 560); National grid series 1956-57 (1:10 560); 1974-1980 (1:10 000); and air photographs: 1995 (Natural England, 25 cm resolution), 2003-04 and 2009-10 (source: © Bluesky International Ltd, 25 cm resolution). These historic maps and air photographs have a full coverage of the Lake District upland study region and cover the period of the last *c.* 150 years. Bedrock and superficial geology data (British Geological Survey, 2016) provides an indication of the availability and calibre of sediment and resistance to erosion. Land cover influences surface runoff and sediment availability to a channel, and therefore the potential for channel adjustment (Rowland et al., 2017). Historic maps, air photographs, DTM, geology and land cover are available as georeferenced files and can be analysed in a Geographical Information System (GIS). There are 19 flow gauges in the Lake District upland region. The earliest flow gauge 1935 – present is on St John's Beck (NGR NY 313 195). Historical flood events in the region are documented in archival records (newspapers, local reports) and represent an important source of information for understanding potential climate influences on discharge and channel adjustment over the past 150 years (Watkins and Whyte, 2008). The available data allows patterns and geomorphic variables of planform adjustments to be assessed spatially and temporally across the Lake District upland region.

3.9 Chapter conclusions

This chapter describes the characteristics of the Lake District upland study site in north-west England. The Lake District has an active fluvial system and patterns of sediment continuity and planform adjustment are influenced by the regional geology, glacial legacy, prevailing climate and anthropogenic activity (Wilson, 2010). Figure 3.15 summarises the exogenic variables influencing river channel planform adjustment and the available data in the Lake District since 1650s (modified from Higgitt et al., 2010). Over the past *c.* 150 years there has been an intensity of change in exogenic controls on planform stability. For example, climate has warmed which has been associated with an increase in extreme flood events (Chiverrell et al., 2019), (Fig. 3.15). Mining and quarrying was historically the main industrial activity (1600s - 1940s), however has since decreased in extent (LDNPA, 2017). Slate quarrying, sheep farming and tourism now remain the main land uses within the region. Anthropogenic activities have directly modified high order channels through channelization, river restoration (Fig. 3.10) and flow regulation. Indirectly, changes in land use (e.g. mining, farming, forest clearance) has instigated increases in sediment supply from valley slopes to the channels (Fig. 3.15). The Lake District has available historic maps and air photographs, and flow data (Table 3.4), which can provide an understanding of planform adjustment over the era of measurable change. The Lake District therefore is a suitable case study to investigate the complexities of historic river channel planform adjustments outlined in Chapters 1 and 2. This Chapter has presented the study catchments which are the focus of Chapters 4, 5 and 6. Chapter 4 explores the reach scale patterns of sediment continuity along St John's Beck in response to the extreme storm Desmond flood event.

Table 3.4. Available data for assessing patterns and controls of planform adjustment and stability in the Lake District study region.

Data	Date	Scale / Resolution	Source
DTM	2016	5 m	Edina Digimap
Ordnance Survey map	2016	1:10 000	Ordnance Survey
Historic maps	1860s	1:10 560	Ordnance Survey County Series 1st ed. – 3rd revision
	1950s	1:10 560	National Grid Imperial 1st Edition. (1st – 3rd Revision)
	1980	1:10 000	National Grid 1:10,000 series, fully metric, 1st edition

Table 3.4. continued.

Data	Date	Scale / Resolution	Source
Air photographs	1995	0.25 m	Natural England
	2004	0.25 m	Bluesky International Ltd
	2010	0.25 m	Bluesky International Ltd
Land Cover	2015	25 m	Rowland et al., 2017
Bedrock Geology		1:50 000	British Geological Survey, 2016
Superficial Geology		1:50 000	British Geological Survey, 2016
Flow Data	1940s-present	Daily	Environment Agency, 2017
Rainfall data	1900-present	Monthly	Met Office Centre of Ecology and Hydrology (Tanguy et al., 2019)

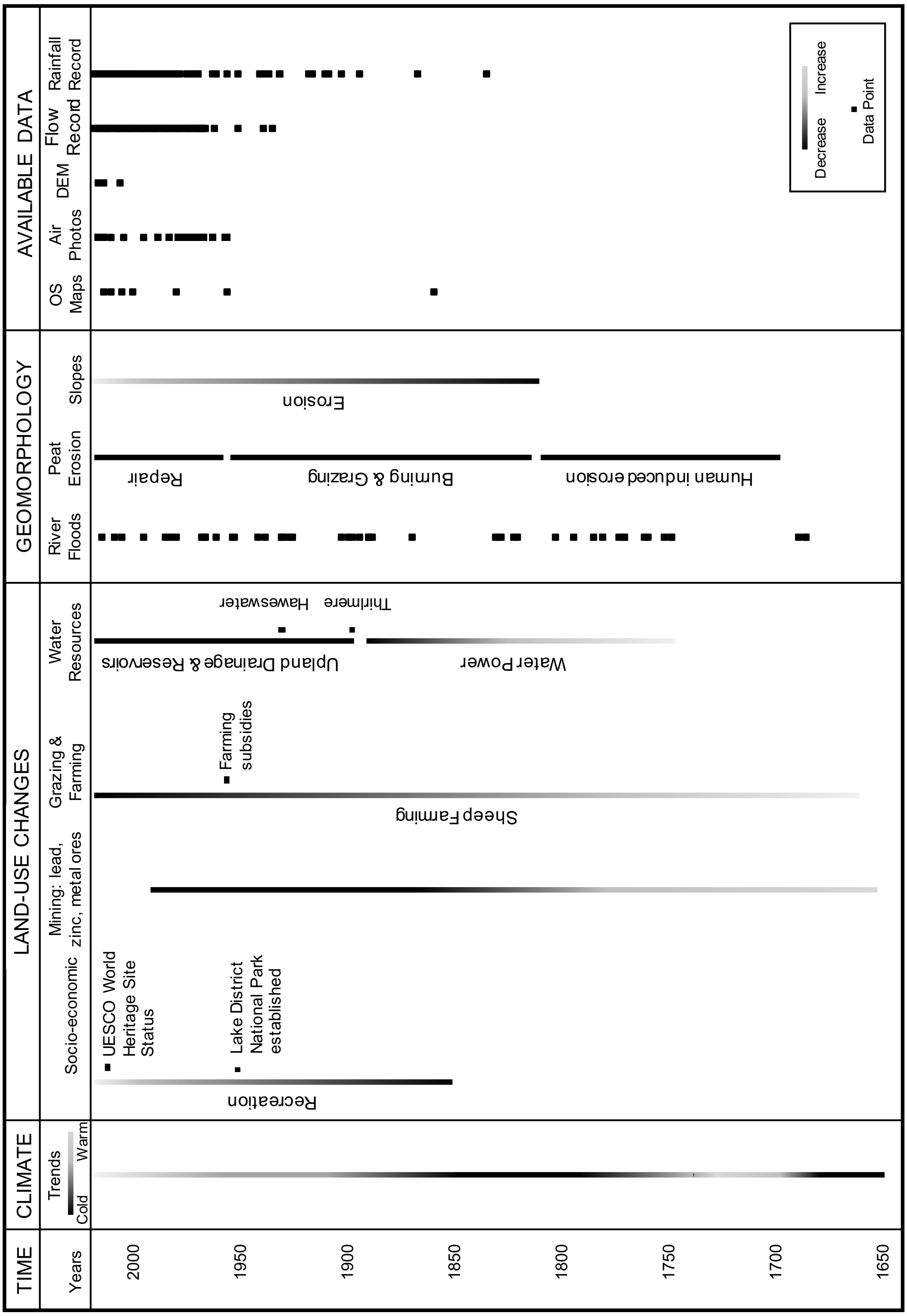


Figure 3.15. Summary of change since 1650 in climate, land use and geomorphology in the Lake District region (modified from Higgitt et al., 2001)

Chapter 4

Sediment continuity through the upland sediment cascade: geomorphic response of an upland river to an extreme flood event

Published paper:

Joyce, H.M., Hardy, R.J., Warburton, J. and Large, A.R., (2018). Sediment continuity through the upland sediment cascade: geomorphic response of an upland river to an extreme flood event. Geomorphology, 317, pp. 45-61.

4.1 Chapter summary

Hillslope erosion and accelerated lake sedimentation are often reported as the source and main stores of sediment in the upland sediment cascade during extreme flood events. While upland valley floodplain systems in the transfer zone have the potential to influence sediment continuity during extreme events, their geomorphic response is rarely quantified. This Chapter quantifies the sediment continuity through a regulated upland valley fluvial system (St John's Beck, Cumbria, UK) in response to the extreme Storm Desmond (4-6 December, 2015) flood event. A sediment budget framework is used to quantify geomorphic response and evaluate sediment transport during the event. Field measurements show 6500 ± 710 t of sediment was eroded or scoured from the river floodplains, banks and bed during the event, with 6300 ± 570 t of sediment deposited in the channel or on the surrounding floodplains. Less than 6 % of sediment eroded during

the flood event was transported out of the 8 km channel. Floodplain sediment storage was seen to be restricted to areas of overbank flow where the channel was unconfined. Results indicate that, rather than upland floodplain valleys functioning as effective transfer reaches, they instead comprise significant storage zones that capture coarse flood sediments and disrupt sediment continuity downstream.

4.2 Introduction

Upland rivers are active geomorphic systems that generate some of the highest annual global sediment yields (Milliman and Syvitski, 1992). The steep channel gradients, high runoff and dynamic geomorphic processes result in high rates of sediment production, transfer, deposition and geomorphic change (Johnson and Warburton, 2002; Warburton, 2010). These processes are greatest during high magnitude, low frequency, extreme flood events when sediment yields can increase by orders of magnitude, even when averaged over centennial to millennial timescales (Korup, 2012; Wicherski et al., 2017). The geomorphic impacts of these extreme events such as riverbed and bank erosion (Prosser et al., 2000; Milan, 2012; Thompson and Croke, 2013), channel widening (Krapesch et al., 2011), overbank sediment deposition (Williams and Costa, 1988; Knox, 2006), floodplain scour (Magilligan, 1992) and the destruction of protection structures (Langhammer, 2010) can have significant impacts on upland river valleys and surrounding society and infrastructure (Davies and Korup, 2010). Many of these upland systems have been anthropogenically modified to minimise the geomorphic impacts of 1 in 100 year flood events (Hey and Winterbottom, 1990; Gergel et al., 2002), but under extreme flows managed river corridors can be reactivated.

Previous research has focused on understanding the controls of such geomorphic change during extreme events to help better predict and manage the impacts. For example, studies have explored the potential for geomorphic work through magnitude-frequency relationships (Wolman and Gerson, 1978), hydraulic forces (i.e., discharge, shear stress, stream power (Magilligan, 1992; Thompson and Croke, 2013)), catchment characteristics such as valley confinement (Righini et al., 2017), the role of engineered structures (Langhammer, 2010) and anthropogenic modifications (Lewin, 2013). However, only a few studies (Trimble, 2010; Warburton, 2010; Warburton et al., 2016) have investigated the geomorphic impacts of extreme events in terms of sediment continuity through the upland sediment cascade (USC).

The movement of coarse sediment in and between the zones of the USC has been compared to a 'jerky conveyor belt' (Ferguson, 1981; Newson, 1997) where sediment is transferred and stored over a range of temporal scales. Sediment stores can fuel or buffer sediment transport rates and therefore influence sediment continuity and potential geomorphic change downstream; this is particularly relevant during less frequent higher magnitude events where sources and stores of sediment can rapidly change over a short period of time (Davies and Korup, 2010; Fryirs, 2013). However, the continuity of sediment transfer through intervening modified valley systems has only rarely been directly surveyed or evaluated in detail after extreme flood events (i.e., Johnson and Warburton 2002; Warburton, 2010) and few studies have looked at how these systems recover following these extremes (Milan, 2012).

Understanding sediment continuity and planform adjustments during extreme events in upland valley systems will become increasingly important for hazard management given projected increases in winter precipitation from predicted climate change (Raven et al., 2010; van Oldenborgh et al., 2015). However, extreme flood events are difficult to predict (Lisenby et al., 2018) and there are few direct measurements from these events. Consequently, their impacts have to be inferred from historical information and estimates of the quantity of sediment stored and transported are generally poorly constrained.

This Chapter quantifies the geomorphic response of an upland river valley system (transfer zone) to Storm Desmond, an extreme flood event that hit Cumbria, north-west England, in December 2015. Specifically, the objectives of this Chapter are to (i) quantify the geomorphic impacts of the extreme event on the upper floodplain valley system of the USC; (ii) estimate bedload sediment transport rates during the flood; (iii) evaluate system recovery one year after the flood event; and (iv) place findings within the wider context of sediment continuity through the USC. This study will enable better understanding of sediment continuity in upland regions at the channel scale.

4.3 Study site

This study focused on St John's Beck, an 8 km channelized, regulated gravel bed river downstream of Thirlmere Reservoir, Central Lake District, UK (NGR NY 318 203, catchment area including Thirlmere Reservoir is 53.4 km^2, effective catchment area is 12 km^2), (Fig. 4.1a). St John's Beck is a tributary to the River Greta that flows through the town of Keswick before discharging into Bassenthwaite Lake (area = 5.1 km^2). St John's Beck ranges in altitude from 178 m OD at the Thirlmere Reservoir outlet to 130 m OD where it joins the River Greta (Fig. 4.1a). St John's Beck lies in the upper floodplain transfer zone of the USC (Fig. 4.1b). The channel has a Strahler (1952, 1957) stream order of 3, mean channel slope of 0.005 and mean channel width of 12 m. St John's Beck lies in a glaciated valley (Vale of St John's) that is underlain by Ordovician Borrowdale Volcanic rocks in the north of the catchment and the Skiddaw group in the south. The land surrounding the channel is predominantly mixed woodland and pasture used for livestock grazing. St John's Beck is a Site of Special Scientific Interest and lies in the Derwent and Bassenthwaite Lake Special Area of Conservation. The river is protected to support salmon, lamprey species, otters and floating water plantain (Wallace and Atkins, 1997; Reid, 2014).

St John's Beck has a wandering planform, which has been restricted laterally due to channelization in the late nineteenth century following the impoundment of Thirlmere Reservoir (area = 3.3 km^2). The channel is confined by the natural valley topography in the upstream reaches. Floodplain valley width increases 1.8 km downstream from Thirlmere Reservoir (Fig. 4.1a), however the river channel has been modified and restricted from movement here (1.8 - 5 km downstream) through bank reinforcement and flood protection levees. Flood protection levees were built to protect farmland and a major link road from flooding. Long-term flow regulation has influenced sediment transport rates in St John's Beck and as a result the system displays clear zones of aggradation. There are four first order tributaries that flow into St John's Beck. Flow and sediment are intercepted from two of these tributaries, which drain the Helvellyn mountain range and are directed to Thirlmere Reservoir (Reid, 2014; Bromley, 2015). The third and fourth first order tributaries are constrained by the presence of a road and a sediment trap and therefore are not a major source of sediment to St John's Beck.

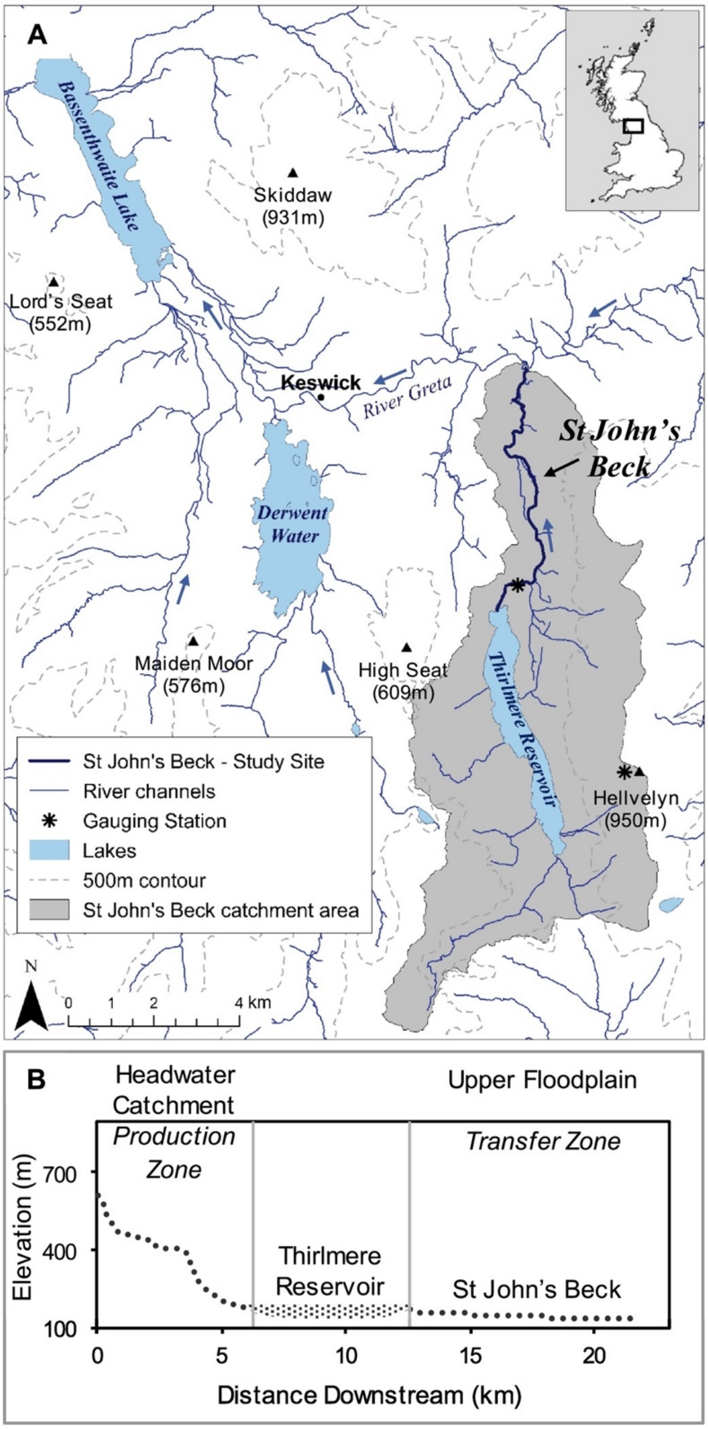


Figure 4.1. St John's Beck study site and position in the upland sediment cascade. (A) Location and catchment area of St John's Beck, Cumbria, UK, identifying the study reach and catchment discharge and rainfall gauging stations. Arrows indicate flow direction. (B) Long profile through the St John's Beck catchment showing the interruption of Thirlmere Reservoir on the USC.

4.4 The Storm Desmond flood event

Extreme flood events in the Lake District have been documented from 1690 to the present (Watkins and Whyte, 2008) (recent floods summarised in Table 4.1). This chapter describes the geomorphological impacts of the Storm Desmond (4-6 December 2015) flood event. Storm Desmond, a North Atlantic storm, was associated with a mild and moist slow moving low pressure system located northwest of the UK that brought severe gales and exceptionally persistent heavy rainfall over northern UK (Met Office, 2016). Northern England experienced the wettest December on record (in a series from 1910), following the second wettest November, after 2009 (McCarthy et al., 2016). The average December rainfall doubled in northern England, with the Lake District receiving three times its average monthly rainfall (McCarthy et al., 2016). Storm Desmond produced record-breaking rainfall maximums in the UK: 341.4 mm rainfall was recorded in a 24 hour period at Honister Pass (NGR NY 225134), Western Lake District, and 405 mm of rainfall was recorded in a 38 hour period at Thirlmere (chapter study catchment), central Lake District (NGR NY 313 194). The storm was the largest in the 150 year local Cumbrian rainfall series (1867 – 2017), and exceeded previous records set in the 2005 and 2009 Cumbrian floods. The estimated return period for the rainfall event was 1 in 1300 years (CEH, 2015) based on the FEH13 rainfall frequency model (Stewart et al., 2014). The UK climate projection change scenarios for northwest England predict winter flood events like this will occur more often in the future because of increases in rainfall intensity due to climate change (Watts et al., 2015).

4.4.1 Storm Desmond impacts

Storm Desmond caused widespread disruption across northern England, and in particular in upland areas in the Lake District region. The event captured national attention when extreme weather conditions prompted a full-scale emergency response to extreme flooding, erosion and sediment movement by upland rivers. Over 5000 homes were flooded, access routes were destroyed (257 bridges destroyed) and key infrastructure was affected, including the erosion of the main A591 trunk road through the central Lake District. The latter was estimated to cost the local economy £1 million per day (BBC, 2016). In the production zone of the USC, saturated hillslopes and high pore-water pressures triggered landslides in a number of valleys, with sediment eroded and transported through mountain torrents (Warburton et al., 2016). Geomorphic impacts in the upper floodplain system of the USC included the erosion of riverbed and banks, floodplain scour, scour around man-made structures (bridges, levees) and extensive deposition of coarse sediment across floodplains. Storm Desmond caused severe flooding and substantial geomorphic change along St John's Beck (Fig. 4.2).

Table 4.1. Recent flood events in Cumbria, UK, including the 24-h rainfall total (mm) and 24-h rainfall return period (yr).

Date of Event	Rainfall (mm) in 24-h period	Estimated 24-h Rainfall Return Period (yr)	Reference
31 January 1995	163.5	80	Johnson and Warburton (2002)
7-8 January 2005	173	100	Roberts et al. (2009); Environment Agency, (2006)
18-20 November 2009	316.4	480	Sibley (2010); Stewart et al. (2010); CEH (2015)
Storm Desmond, 4–6 December 2015	341.4	1300	CEH (2015)

4.4.2 Hydrological regime in St John's Beck

Flooding is not unusual in St John's Beck, historic accounts describe a *"most dreadful storm... with such a torrent of rain, [which] changed the face of the country and did incredible damage in [St John's in the Vale]"* in 1750, (Smith, 1754). This historical event has characteristics similar to that of Storm Desmond, with large boulders of sediment being transported and deposited on floodplains along the transfer zone. Long term rainfall records available for the St John's Beck Catchment (Fig. 4.3a, Helvellyn Birkside gauging station NGR NY 338 133, ~6.3 km south of St John's Beck; Fig. 4.1) show Storm Desmond contributes to the greatest monthly rainfall event (1361 mm rainfall in December 2015) being five times higher than the mean December rainfall total in the 150 year time series. The rain gauge on St John's Beck (NGR NY 313 195; Fig. 4.1) shows the rain that fell during December 2015 fell on previously saturated ground, following a total of 559 mm in November 2015 (Fig. 4.3b). These antecedent conditions comprise the second wettest November recorded at this site after the 2009 floods (Met Office, 2016).

Daily rainfall totals (Fig. 4.3c) show the event peaked on 5 December 2015, where over a 15 min peak period, an estimated 6.8 mm of rain was recorded. Discharge records for St John's Beck (Fig. 4.4a) similarly show Storm Desmond was the largest magnitude event in the 82 year flow record with an estimated peak discharge recorded during the event of 75.4 $m^3 s^{-1}$ (Fig. 4.4b). Mean discharge for St John's Beck during the 82 year record period is 0.85 $m^3 s^{-1}$; in 2015 mean discharge was 2 $m^3 s^{-1}$.

Figure 4.2. Photographs of the impacts of Storm Desmond along St John's Beck and the surrounding floodplains. (A–B) Flood sediments and debris (tree trunks) transported and deposited on floodplains and in the channel. (C–D) Floodplain scour. (E) Riverbank erosion. (F) Destruction of the access bridge over St John's Beck to Low Bridge End Farm (bridge approximately 3.5 m high for scale).

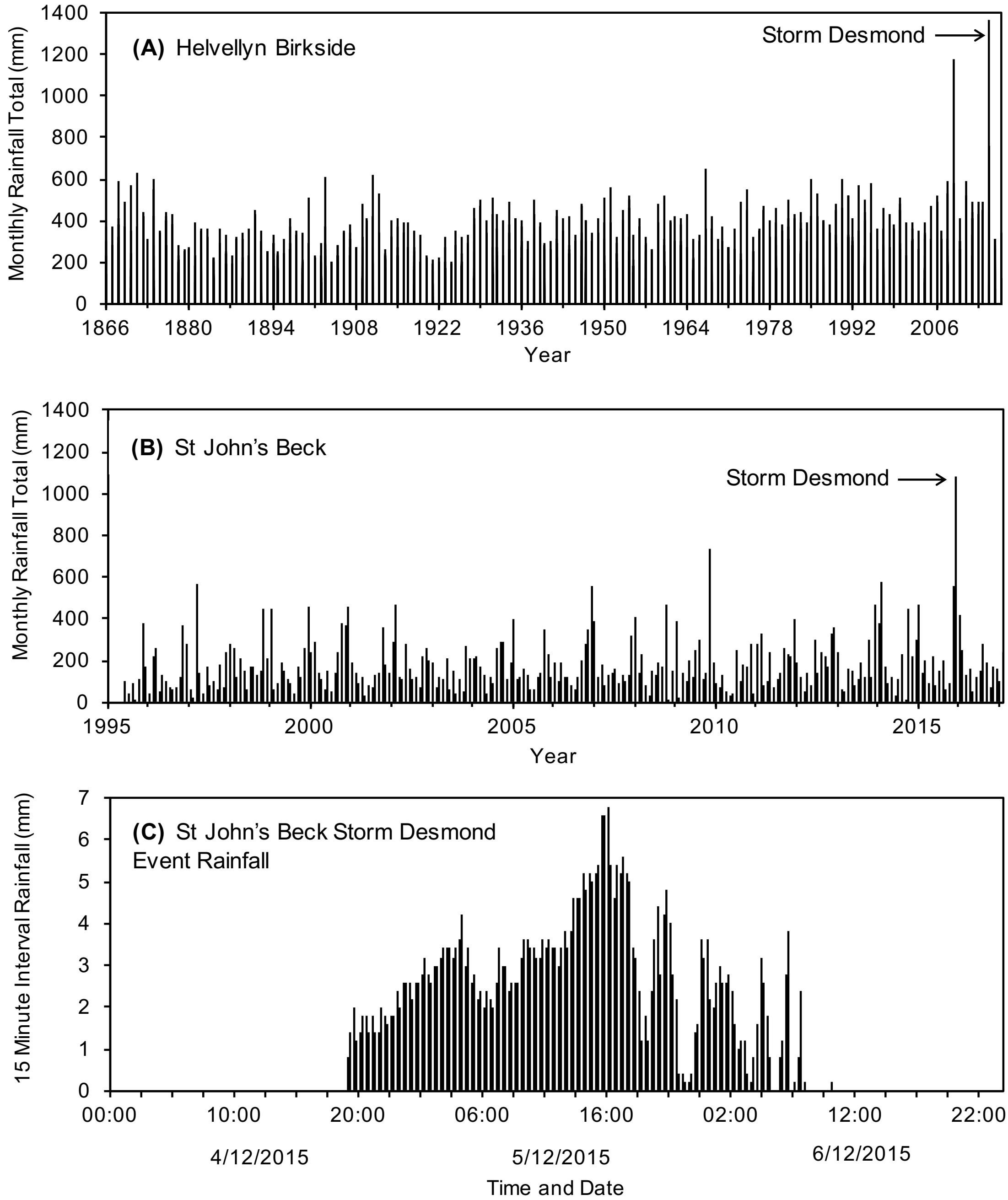


Figure 4.3. Rainfall records in the St John's Beck catchment. (A) Long term (1860 – 2017) monthly rainfall variability in the St John's Beck catchment from the Helvellyn Birkside rain gauge (NGR NY 338 133). (B) Monthly rainfall totals from the St John's Beck Environment Agency (EA) tipping bucket rain gauge (TBG) from 1995-2017. (C) 15 min interval rainfall record from St John's Beck EA TBG (NGR NY313 195) during the Storm Desmond flood event.

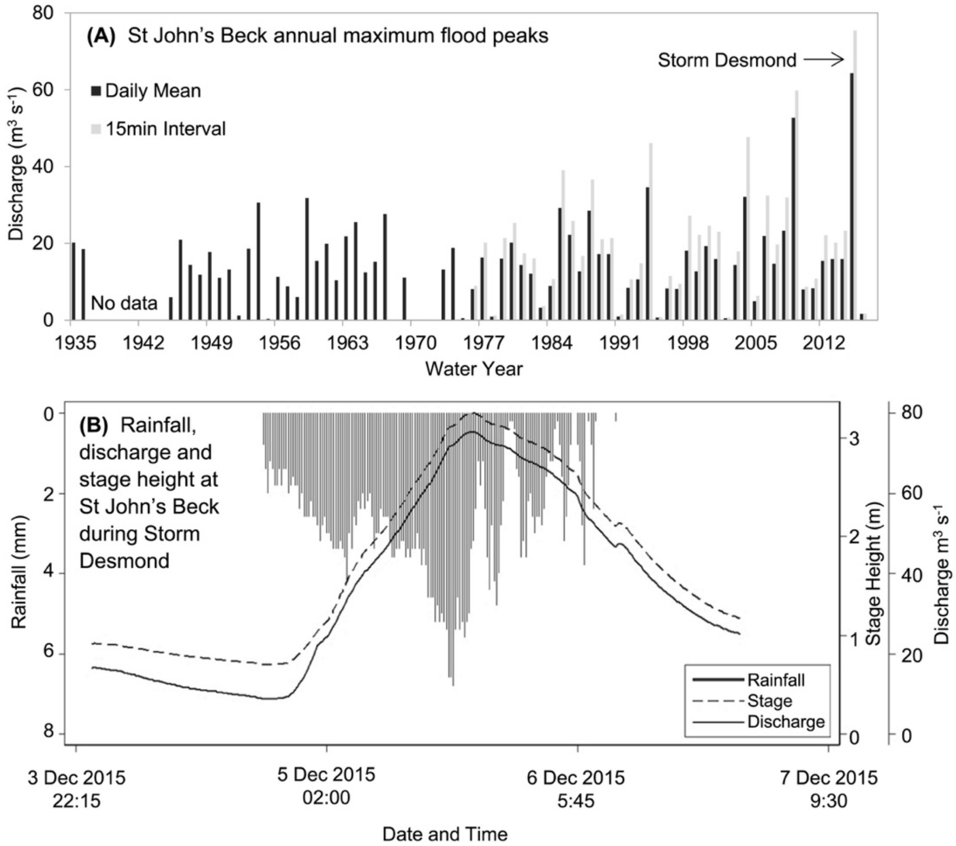


Figure 4.4. Discharge records for the St John's Beck gauging station. (A) Annual maximum flood peaks for St John's Beck gauging station 1935-2016 using daily mean and 15 min interval recorded flow data. (B) Estimated discharge, stage height and total rainfall during Storm Desmond.

4.5 Methods

This chapter analyses geomorphic data collected during two field campaigns at St John's Beck. The first survey was completed after the Storm Desmond flood (April-May 2016) to capture the geomorphic impacts of this event before clean-up operations and reworking of flood sediments occurred. The second survey was conducted in June 2017 to assess short-term system recovery following the flood. All field data were digitised and analysed in a GIS in British National Grid coordinates. A 5 m resolution digital terrain model (DTM) (Edina Digimap, 2016), pre-flood aerial imagery, 2009-2011, (from Bluesky International Limited, resolution 0.25 m) and post-flood event, May 2016, (from the Environment Agency, resolution 0.2 m) were used for validating field measurements and to assess valley topographic and local controls of the geomorphic impacts observed.

4.5.1 Geomorphic analysis

4.5.1.1 Channel geometry and bed material

A Leica Geosystems Real Time Kinetic differential GPS (RTK dGPS) 1200, was used to survey channel cross section geometry, floodplain geometry and thalweg long profile during the 2016 and 2017 surveys. Cross section sites were chosen along the 8 km river where there was a clear change in channel geomorphology identified by a walk-over reconnaissance of the catchment in 2016. A total of 22 sites for cross section surveys were chosen along St John's Beck. Cross section 1 was located near the St John's Beck gauging station (1 km downstream from Thirlmere Reservoir), so all data collected could be discussed in relation to the flow and rainfall records (Figs. 4.4b, 4c, and 4.5). The last cross section was located near the confluence with the River Greta (7.8 km downstream). Ten of the cross section sites were located along a 1.3 km length reach where significant riverbank erosion and overbank flood sediment deposition occurred during Storm Desmond. Survey pegs were positioned at the endpoints of each cross section in 2016 and used as control points to allow resurvey in 2017. Cross section profile RTK dGPS measurements had a mean accuracy of ± 0.02 m and standard deviation of 0.06 m in the 2016 survey, and a mean accuracy of ± 0.03 m and standard deviation of 0.03 m in the 2017 survey. Bankfull channel cross-sectional area was calculated at each cross section and changes in channel bankfull capacity ($m^2\ yr^{-1}$) were calculated by differencing the data collected over the survey periods. Thalweg long profile was surveyed using the RTK dGPS. Average profile point spacing was 8 m (mean accuracy of ± 0.02 m and standard deviation of 0.01 m) in the 2016 survey and 12 m (mean accuracy of ± 0.03 m and standard deviation of ± 0.01 m) in the 2017 survey.

Channel surface bed material was measured at each cross section following the pebble count method for grain size distribution (GSD) in the 2016 and 2017 field campaigns. The b-axis of 100 particles were randomly measured (particle under tip of the toe method; Wolman, 1954) along the width of each cross section. The median diameter grain size (D_{50}) and the 90^{th} percentile (D_{90}) were calculated and used to understand system response and sediment transfer following the event.

4.5.1.2 Bedload transport

Bedload sediment transport during Storm Desmond was estimated using the Bedload Assessment for Gravel-bed Streams (BAGS) software (Pitlick et al., 2009) applying a surface-based bedload transport equation (Wilcock and Crowe, 2003). The input parameters were: the GSD of the channel bed surface, cross-sectional data including floodplains, cross section averaged bed elevation slope, flow discharge in the form of a flow exceedance curve for the event, and Manning's 'n' values for a clean winding channel (0.04) and short grass floodplains (0.03) estimated from Chow (1959). Sensitivity to Manning's 'n' values was assessed using Chow (1959) minimum and maximum values for the channel and floodplains. Morphological change between cross sections was calculated by subtracting the downstream cross section bedload transport rate from the upstream value to identify net erosion and deposition reaches.

Historical bedload sediment transport rates were also estimated using the BAGS model (i) as an average daily transport rate for the long-term daily discharge record 1935-2015, and (ii) for the top five discharge events in the long term (15 min interval) flow record. Whilst this assumes that the cross-sectional profiles and grain size distribution are the same as the post-Desmond channel, this analysis allows us to assess the importance of the Storm Desmond event on sediment transport rates in relation to the longer-term system history.

4.5.2 Geomorphic impacts of the Storm Desmond event: sediment budget analysis

A sediment budget framework was used to quantify the geomorphic impacts of the Storm Desmond event and identify the dominant stores of sediment along St John's Beck. Sediment budgets focus on quantifying the erosion, deposition and transfer of sediment through a channel or reach over an event or time period (Reid and Dunne, 1996; Brewer and Passmore, 2002; Fuller et al., 2003). Sediment budgets represent the conservation of mass and can be summarised as (Slaymaker, 2003):

$$O_S = I_s + \Delta S_s \quad (1)$$

where O_s is the sediment output (yield) of the reach, I_s is input of sediment from dynamic sediment sources, and S_s is sediment stored on floodplains, channels etc. This framework is useful to understand local sediment continuity in response to a particular event and indicate whether a system is balanced (Reid and Dunne, 2003). The main geomorphic depositional (S_s) and erosional (I_s) features identified after Storm Desmond along St John's Beck were: floodplain sediment deposits, in-channel bars, floodplain scour, channel bed scour and riverbank erosion (Fig. 3). Floodplain scour is differentiated from bank erosion as it is associated with the stripping of the floodplain surface (vegetation) and removal of large blocks of sediment (Nanson, 1986); whereas bank erosion is defined as the removal of sediment from the bank by hydraulic action or through mass failure (Odgaard, 1987; Knighton, 1998). The volume and sediment size distribution of erosional and depositional components were measured using the RTK dGPS, and pebble count technique (Wolman, 1954) and their spatial extent was validated using the pre- and post-event aerial photographs. Channel bed scour was active during the event, however, it was not directly measured as no cross sections were monumented prior to Storm Desmond. During flood events some reaches can experience scour whilst other reaches aggrade (Reid and Dunne, 1996). The location of channel bed scour was assumed to occur where riverbank erosion or floodplain scour was observed after Storm Desmond; this was quantified using the post-event air photo and field data in GIS. The depth of channel bed scour was estimated according to Carling's (1987) scour-depth relation for gravel bed rivers:

$$d_s = 0.043Q^{0.27} \quad (2)$$

where d_s is depth of scour (m) and Q is the event peak discharge (m^3 s^{-1}).

Volumes of sediment eroded and deposited for each geomorphic component were converted to sediment mass using local values of coarse sediment bulk density of 1860 ± 17 kg m^3 derived from the mean bulk density of 30 measured samples from the channel bed and floodplain sediment deposits.

Sediment input and output of St John's Beck during the event was estimated by converting the BAGS estimated event bedload sediment transport rates into (cross section 1, 1 km downstream) and out of St John's Beck (cross section 22, 7.8 km downstream) into the event sediment yield. Error in sediment budgets represents a combination of survey measurements and calculations, so standard methods of error analysis are difficult to apply. Often, sediment budget error is calculated as an unmeasured residual by subtracting the erosion and deposition components (Kondolf and Matthews, 1991; Reid and Dunne, 2003). As a result, sediment budgets may balance only because errors are hidden in the residual terms (Kondolf and Matthews, 1991). To avoid misrepresentation of the sediment balance, in this study the standard error was calculated for each measurement technique for each geomorphic component. The standard errors were summed and then converted to a percentage before being converted to mass (t) for each component. For example, floodplain deposit mass error represents a combination of errors from the RTK dGPS, depth of deposit, and bulk density error measurements. The standard error from these measurements was calculated and then summed to calculate the total error percentage before being converted to the mass error (t).

4.5.3 Factors controlling geomorphic change

4.5.3.1 Lateral channel confinement ratio

Channel confinement describes the extent to which topography, such as hillslopes, river terraces and artificial structures, limit the lateral mobility of a river channel (Nagel et al., 2014). Lateral channel confinement ratio (C) was calculated as:

$$C = \frac{w_f}{w_c} \tag{3}$$

where w_f is the floodplain width and w_c is the active channel width. Floodplain width (pre- and post-Storm Desmond) is defined as the horizontal distance from the top of the channel bank to the base of the hillslope (Gellis et al., 2017); this is determined using the 2009-2011 and 2016 aerial photographs, the 5 m resolution DTM and the 2016 field data. The active channel width was measured (1) prior to Storm Desmond using the 2009-2011 aerial photographs, and (2) after Storm Desmond using the RTK dGPS channel cross section measurements and May 2016 aerial photographs. Channel and floodplain width were measured at the 22 cross section sites.

Hall et al. (2007) documented that confined channels have a confinement ratio of ≤3.8 and unconfined channels a ratio of >3.8. Channel confinement can influence the potential for sediment erosion and deposition; for example, Thompson and Croke (2013) found that in a high magnitude flood event in the Lockyer Valley, Australia, erosion was concentrated in the confined reaches, and deposition was concentrated in unconfined reaches with floodplains acting as a major store of sediment. Such behaviour may be affected by the presence of structures such as levees or roads, which are present along St John's Beck. Three types of confinement were identified along St John's Beck: (1) natural confinement, defined as the channel confinement by the natural valley bottom topography; (2) artificial confinement, where reaches of the channel have been modified through reinforced riverbanks, the presence of walls, levees, or road embankments that prevent the channel from migrating laterally; and (3) the post-Storm Desmond confinement taking into consideration the active channel width following the extreme event.

4.5.3.2 Stream power and shear stress

At the reach scale average shear stress, Eq. (4) (Du Boys, 1879), critical shear stress, Eq. (5) (Gordon et al., 1992), unit stream power, Eq. (6) (Bagnold, 1966) and critical unit stream power Eq. (7) (Bagnold, 1966; Williams, 1983; Petit et al., 2005) were calculated for the Storm Desmond flood to understand the potential magnitude of sediment transport rates and geomorphic impacts observed during the event using the one-dimensional uniform flow approximations:

$$\tau = \rho g d S \tag{4}$$

$$\tau_c = 0.97 D_i \tag{5}$$

$$\omega = \frac{\rho g Q S}{w} \tag{6}$$

$$\omega_c = 0.079 D_i^{1.3} \tag{7}$$

where τ is the reach averaged shear stress (N m^{-2}), ρ is the density of water (kg m^{-3}), g is the acceleration of gravity (m s^{-2}), S is channel bed slope (m m^{-1}) and d is the maximum water depth during the event (m). τ_c is the critical shear stress (N m^{-2}) and D_i is the grain size (mm). Here the channel D_{50} and D_{90} is used. ω is the unit stream power (W m^{-2}), Q corresponds to the peak discharge (m^3 s^{-1}) during Storm Desmond and w (m) is the bankfull width during the flood. ω_c is the critical unit stream power (W m^{-2}) for particle motion based on Williams' (1983) relation for gravel transport in rivers with grain sizes between 10-1500 mm. Calculations were applied at the cross section locations and the critical shear stress ($\tau > \tau_c$) and critical stream power ($\omega > \omega_c$) entrainment thresholds estimated to understand the potential for sediment mobility during the event. Shear stress and stream power calculations were also calculated using the June 2017 survey data (bankfull cross section profiles, grain size data, and mean daily discharge (0.085 m^3 s^{-1}) to quantify variation in shear stress and stream power during non-overbank flows.

4.6 Results

4.6.1 Geomorphic response to the Storm Desmond event

Storm Desmond flood impacts along St John's Beck were concentrated in the channel and on the surrounding floodplains. The spatial distributions of both erosional and depositional impacts of Storm Desmond are shown in Fig. 4.5a. Generally, erosion and deposition impacts were observed in spatially similar locations, for example, where bank erosion or scour occurred overbank deposition was observed. Significant erosion and deposition impacts were observed 1.7–3.6 km downstream of Thirlmere Reservoir (Fig. 4.5b). Geomorphic impacts were less pronounced 3.6-8 km downstream of Thirlmere Reservoir; impacts here were often concentrated locally at meander bends (e.g., as seen at 5.2 km downstream from Thirlmere Reservoir, cross section 18). Figure 4.5b shows a detailed map of the reach where significant geomorphic impacts (1.7–3.6 km downstream) were observed after Storm Desmond. Overbank floodplain deposits and channel bars measured 2.1–2.5 km downstream (between cross sections 7 to 10) occur where the channel is laterally unconfined. The channel in this reach (2.1-2.5 km downstream) was identified as aggradational (low channel capacity, channel bed nearly level with banks) in a reconnaissance survey (approach after Thorne, 1998) of the site prior to the flood. Bank erosion and scour was concentrated on the artificially-confined reach 2.5-3 km downstream (cross sections 10 to 13). Local lateral riverbank recession exceeded 12 m and caused the destruction of flood protection levees 2.7 km downstream of Thirlmere

Reservoir (see cross section 11 Fig. 4.5b). Material eroded at cross section 11 was subsequently deposited on the floodplains downstream.

The dominant geomorphic features surveyed after the event were overbank floodplain sediment deposits. Floodplain sediment deposits located 1.8 km downstream (near cross section 5) were sourced from a tributary and not from St John's Beck. The tributary sediment did not enter St John's Beck due to a wall and sediment trapping structure, therefore, the mass of sediment measured here (300 t) is excluded from the sediment budget analysis. A total of 105 floodplain deposits were identified from St John's Beck, equating to a sediment mass of 4700 ± 300 t. Flood sediment deposits were generally composed of a single layer of sediment with a mean deposit depth 0.09 m ± a standard deviation of 0.07 m; the maximum flood deposit depth measured was 0.3 m located 2.7 km downstream of Thirlmere Reservoir. The mean grain size of sediment deposit D_{50} was 32 mm and D_{90} was 90 mm. The 10 largest clasts from the deposits had a mean grain size of 147 mm ± a standard deviation of 12.5 mm. Flood deposit grain size decreased with distance from the channel. The farthest flood deposit from the channel bank (70 m distance) had a D_{50} of 22 mm and D_{90} of 63 mm. The proximal flood deposits (2 m distance from the channel) had a mean D_{50} of 39 mm ± a 17 mm standard deviation and D_{90} of 111 mm ± a standard deviation of 35 mm.

Table 4.2 shows the variation in grain size between the flood sediment deposits and the channel bed sediments. Channel bed sediment D_{50} is greater than the floodplain sediment deposits, however, this pattern is reversed for sediment D_{90}. Floodplain sediment deposits are composed of material from the channel bed and from eroded features (such as artificial levees and stone walls), which generally have coarser grain sizes that could account for this variation.

Riverbank erosion and floodplain scour were the main processes accounting for a loss of sediment during Storm Desmond. Based on the field data collected, 2300 ± 270 t of sediment was eroded from the riverbanks. Floodplain scour contributed to the removal of 1300 ± 50 t of sediment during the event, 40% of sediment removed through scour was over the reach (2.2-3.6 km downstream) where significant sediment deposition was observed. Local scour of 350 ± 13 t undermined and destroyed the access bridge to Low

Bridge End Farm (see cross section 10, 2.5 km downstream of Thirlmere Reservoir, Fig. 4.5). The depth of channel bed scour was estimated at 0.13 m according to Carling's (1987) scour depth equation, and this equated to a mass of 2900 ± 470 t.

Table 4.2. Grain size (mm) of floodplain deposits and channel bed sediments in the May 2016 and June 2017 survey.

		Floodplain Sediment Deposits	Channel Bed Sediments (2016 Survey)	Channel Bed Sediments (2017 Survey)
	Max	64	77	90
D_{50}	Mean	32	49	53
	Std. Dev.	13	14	18
	Max	181	90	294
D_{90}	Mean	90	53	122
	Std. Dev.	37	17	35

Figure 4.6 displays the total mass of sediment eroded and deposited along St John's Beck during Storm Desmond. The greatest mass of sediment eroded and deposited occurs from 1.7 to 3.6 km downstream where the floodplain width increases from 7 to 450 m and channel slope steepens from 0.001 (0 to 1.7 km downstream) to 0.005 (1.7 to 3.6 km downstream). Erosion features were often balanced by sediment deposition nearby. For example, the largest mass of sediment deposited on floodplains (1340 t) correlates with the area of greatest erosion (980 t) 2.9 km downstream of Thirlmere Reservoir, where a levee was destroyed and the riverbank receded by 12 m resulting in sediment deposition over an area of 3470 m^2. Erosion and deposition impacts are less pronounced 5.2-7.8 km downstream, where the mean floodplain valley width is 77 m ± a standard deviation of 26 m, and the mean channel slope is 0.003. Erosion and deposition impacts at 5.2 - 7.8 km downstream were mainly concentrated on meander bends. Floodplain scour (Fig. 4.2c) and sediment deposition was observed on the inside of a meander bend 5.2 km downstream where overbank flows were permitted during Storm Desmond. Local bank erosion and overbank sediment deposition was observed on bends 6.8 and 7.3 km downstream.

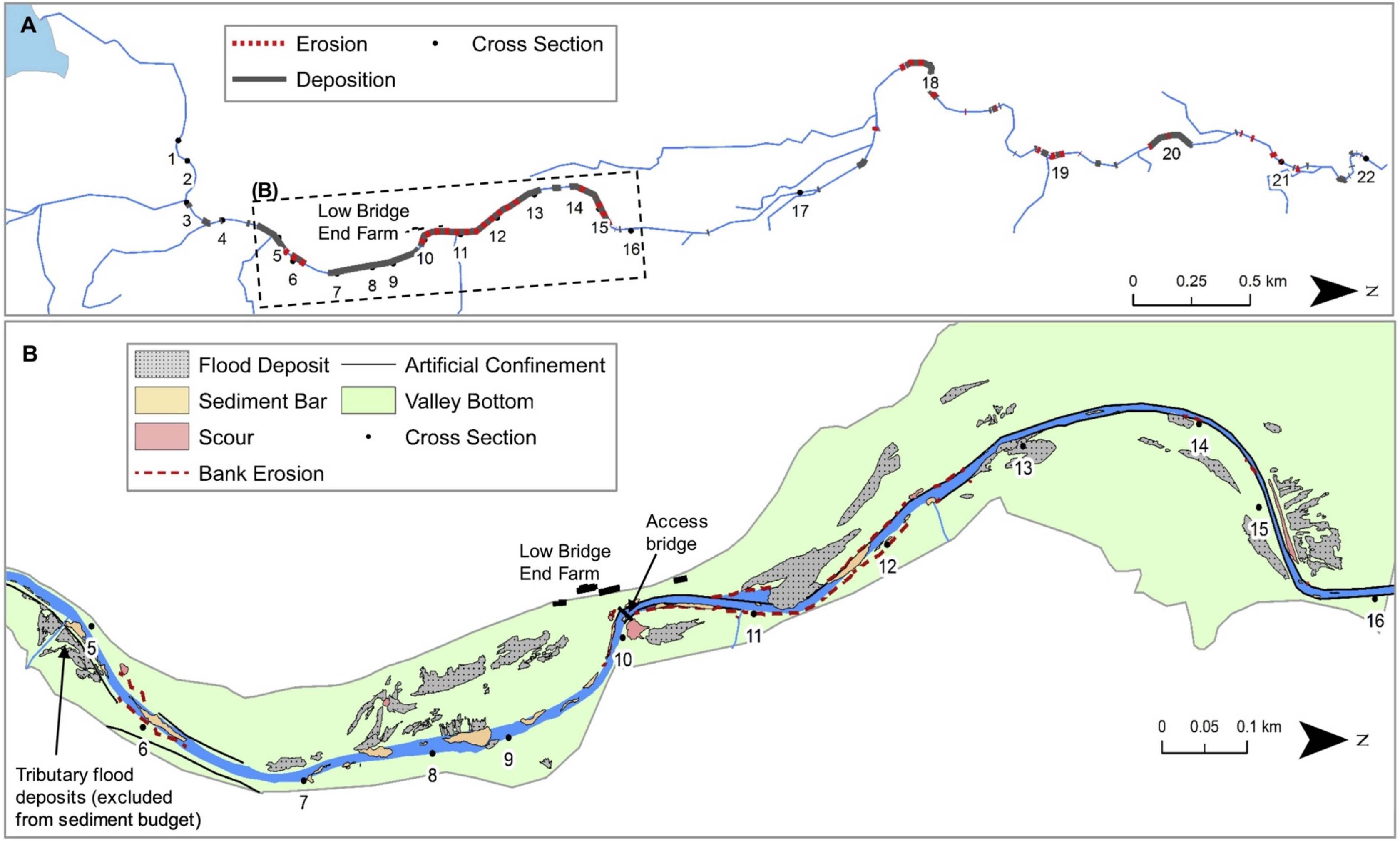


Figure 4.5. Geomorphic impacts of the Storm Desmond flood event along St John's Beck, flow direction North. (A) Location of erosion and deposition impacts along St John's Beck. (B) Detailed geomorphic map showing an example reach (1.7-3.6 km downstream of Thirlmere Reservoir) with erosion and deposition impacts.

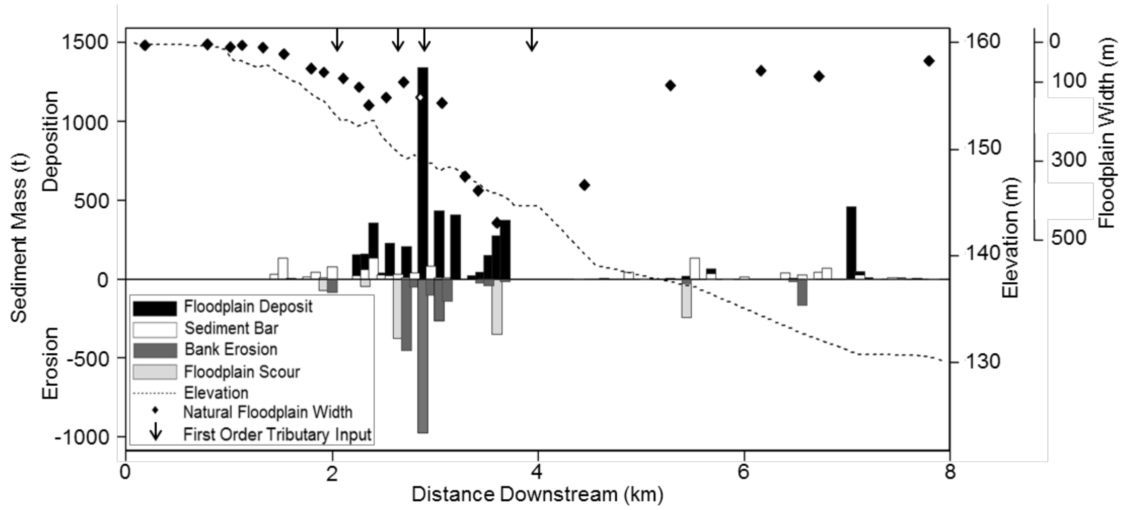


Figure 4.6. Total mass (t) of sediment eroded and deposited along St John's Beck during Storm Desmond, plotted alongside the natural floodplain width and riverbed longitudinal profile.

Tree debris was observed surrounding St John's Beck following Storm Desmond. Tree debris did not cause a blockage around the access bridge to Low Bridge End Farm. However, tree debris was observed in the channel near cross section 10 (2.5 km downstream) (see Fig. 4.2b). The limited occurrence of woody debris in the channel inhibits the formation of log jams and only has local impacts on sedimentation.

4.6.2 Estimates of bedload sediment transport rate

The mean event bedload sediment transport rate for the 22 cross sections was 160 t ± a standard error of 60 t. Sediment transport rates fluctuate downstream with clear reaches of low and high sediment transfer (Fig. 4.7a). For example, 1.5-2 km downstream of Thirlmere Reservoir high sediment transport rates during the event (range = 220-500 t) are estimated; these are attributed to a local increase in channel slope. The maximum estimated transport rate during the event was 1200 t at 2.5 km downstream of Thirlmere Reservoir where the channel widens and local slope increases (slope 0.01) downstream of a ford, near the access bridge to Low Bridge End Farm that was destroyed during the event (Fig. 4.2f). The sediment input into St John's Beck during the event is estimated at 7 t (1 km downstream of Thirlmere Reservoir, cross section 1) and the sediment output (7.8 km downstream of Thirlmere reservoir, cross section 22), during the event is estimated as 370 t.

Zones of erosion and deposition along St John's Beck have been identified by differencing sediment transport rates between the surveyed cross sections (Fig. 4.7b). A total of 10 deposition and 11 erosion zones are defined. The zone of greatest erosion and deposition is located from 1.8 to 4 km downstream from Thirlmere Reservoir (Fig. 4.7b), which corresponds closely with field measurements of erosion and deposition during the event (Fig. 4.5).

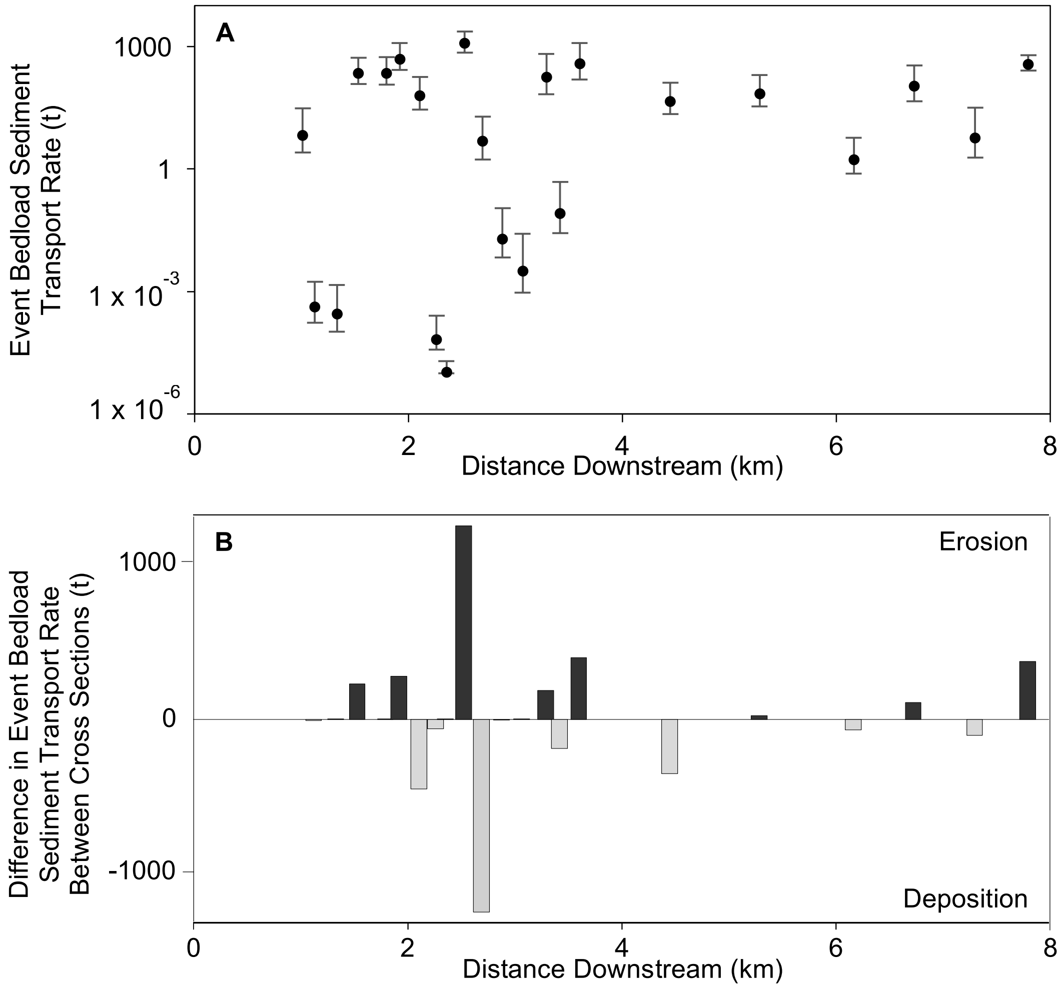


Figure 4.7. Bedload sediment transport estimates along St John's Beck during Storm Desmond. (A) Storm Desmond event bedload sediment transport rates. Error bars plotted represent sensitivity to the maximum and minimum Manning's 'n' values. (B) Zones of sediment erosion and deposition downstream, calculated as the difference between sediment transport rates between cross section survey locations.

The mean daily bedload sediment transport rate (calculated as the mean transport rate from the 22 cross sections using the 1935–2015 discharge record), is 0.05 t day^{-1} with a standard deviation of 0.09 t day^{-1}. The estimated annual bedload sediment input is estimated at 0.5 t yr^{-1} (at cross section 1) and the bedload sediment yield (at cross section 22) is 38 t yr^{-1} for St John's Beck long term discharge record. The bedload sediment output during Storm Desmond (370 t) exceeds the annual value by a factor of 9. Table 3 displays the bedload sediment transport estimates for the top five discharge events in the St John's Beck 15 min interval flow record. The Storm Desmond event produced the highest bedload sediment transport rates in the flow record, nearly double the second highest flood event in 2009.

Table 4.3. Bedload sediment transport estimates for the top five discharge events from the 15 min interval flow series data for St John's Beck. The event bedload transport rates are calculated as the mean transport rate from the 22 cross sections, and the event sediment yield is calculated at cross section 22.

			Event Bedload Sediment Transport Rate (t)			
Date of Event	**Estimated Event Peak Discharge (m^3 s^{-1})**	**Event Rainfall Total (mm)**	**Mean**	**Std. Dev.**	**Max**	**Event Sediment Yield**
4/12/2015 - 6/12/2015	75.4	405.0	157	283	1229	370
17/12/2009 - 20/11/2009	59.8	400.0	91	166	700	210
7/01/2005 - 8/01/2005	47.7	180.0	30	55	188	70
31/01/1995 - 01/02/1995	39.0	-	25	45	151	54
21/12/1985 - 22/12/1985	36.6	-	21	41	142	32

4.6.3 Controlling factors that influenced geomorphic change across the reach

4.6.3.1 Channel Confinement Index

St John's Beck displays different degrees of lateral confinement downstream (Fig. 4.8). The natural channel confinement pattern shows that the channel becomes gradually unconfined downstream (Fig. 4.8). For example, in the upstream reach (0 to 1.8 km downstream of Thirlmere Reservoir) the channel is topographically confined (confinement ratios range from 0.1 to 0.6) and from 4.4 to 8 km downstream the channel is topographically unconfined (confinement ratios range from 5 to 65). The channel has been artificially confined from 1.8 to 4.4 km downstream by flood protection levees, reinforced banks and walls that restrict lateral channel movement. The mean natural floodplain width has been reduced by 90 % due to the presence of artificial structures along the artificially confined reach 1.8 to 4.4 km downstream. During Storm Desmond, many of the artificially-reinforced banks and flood protection levees were scoured or eroded increasing the active channel width and allowing channel-floodplain interactions (Fig. 4.8). After Storm Desmond the mean confinement ratio increased from 0.95 to 17 along the artificially confined reach (1.8 to 4.4 km downstream), indicating the system reverted to a natural floodplain-channel width relationship (Fig. 4.8).

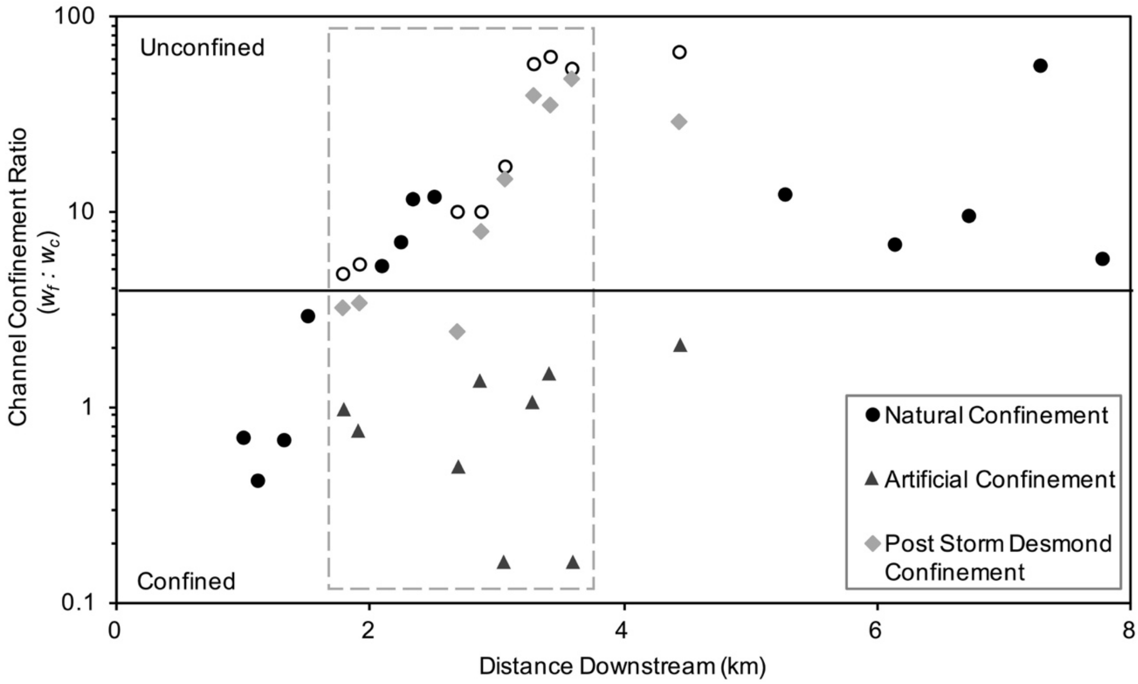


Figure 4.8. Natural, artificial and post Storm Desmond lateral channel confinement ratios along St John's Beck. Hollow circles indicate the natural system if the channel was not artificially confined. The dashed box indicates the area where significant sediment erosion and deposition was observed during Storm Desmond. Continuous line indicates the confined and unconfined threshold.

4.6.3.2 *Shear stress and stream power*

Shear stress and stream power are used to understand the energy expenditure for erosion and sediment entrainment during the event (Fig. 4.9). The shear stress values estimated for Storm Desmond are shown in Fig. 4.9a. The shear stress values estimated should be regarded as minimum values because they assume shear stress is the same on the channel and floodplain and the equations assume steady uniform flow, which was unlikely during the event. The mean shear stress value is 149 N m^2 with a standard deviation of 78 N m^2. The peak shear stress value (426 N m^2) was estimated 2.7 km downstream of Thirlmere Reservoir; near where the access bridge was destroyed and mass overbank coarse sediment deposition occurred. The minimum shear stress values are estimated 1.1 to 1.3 km downstream (30-60 N m^2) where local slope is 0.001. The mean shear stress value exceeded the mean critical entrainment thresholds for particle D_{50} (48 ± a standard deviation of 14 N m^2) and D_{90} (124 ± a standard deviation of 30 N m^2) (Fig. 4.9a), suggesting full mobility of the GSD during the event. The mean shear stress value estimated using the 2017 survey data (62 N m^2 with a standard deviation of 40 N m^2) does not exceed the threshold for mean particle D_{90} (114 N m^2) entrainment and only exceeds 60 % of the cross section particle D_{50} entrainment threshold during bankfull flow conditions.

The unit stream power values estimated along St John's Beck using the peak Storm Desmond discharge value range from 25 to 354 W m^{-2}, with a mean of 230 W m^{-2} and a standard deviation of 132 W m^{-2} (Fig. 4.9b). The values are within the range of stream power values documented for those causing erosion during flood events and sediment transport (Baker and Costa, 1987; Magilligan, 1992; Fuller, 2008; Marchi et al., 2016). A value of 300 W m^{-2} is commonly referred to as a threshold for producing floodplain erosion (Baker and Costa, 1987; Magilligan, 1992; Fuller, 2008). Significant erosion and scour was observed 2.5 km downstream where an access bridge was destroyed and where stream power was estimated at 420 W m^{-2}. The mean unit stream power estimate (230 W m^{-2}) exceeds the critical unit stream power value for particle D_{50} (13 W m^{-2}) and D_{90} (54 W m^{-2}) entrainment, suggesting mobilisation of the coarsest grains. The mean unit stream power, estimated using the 2017 data and mean daily discharge, is 0.26 W m 2 ± a standard deviation of 0.12 W m^{-2}; this value does not exceed the critical stream power threshold for channel bed particle D_{50} and D_{90} entrainment.

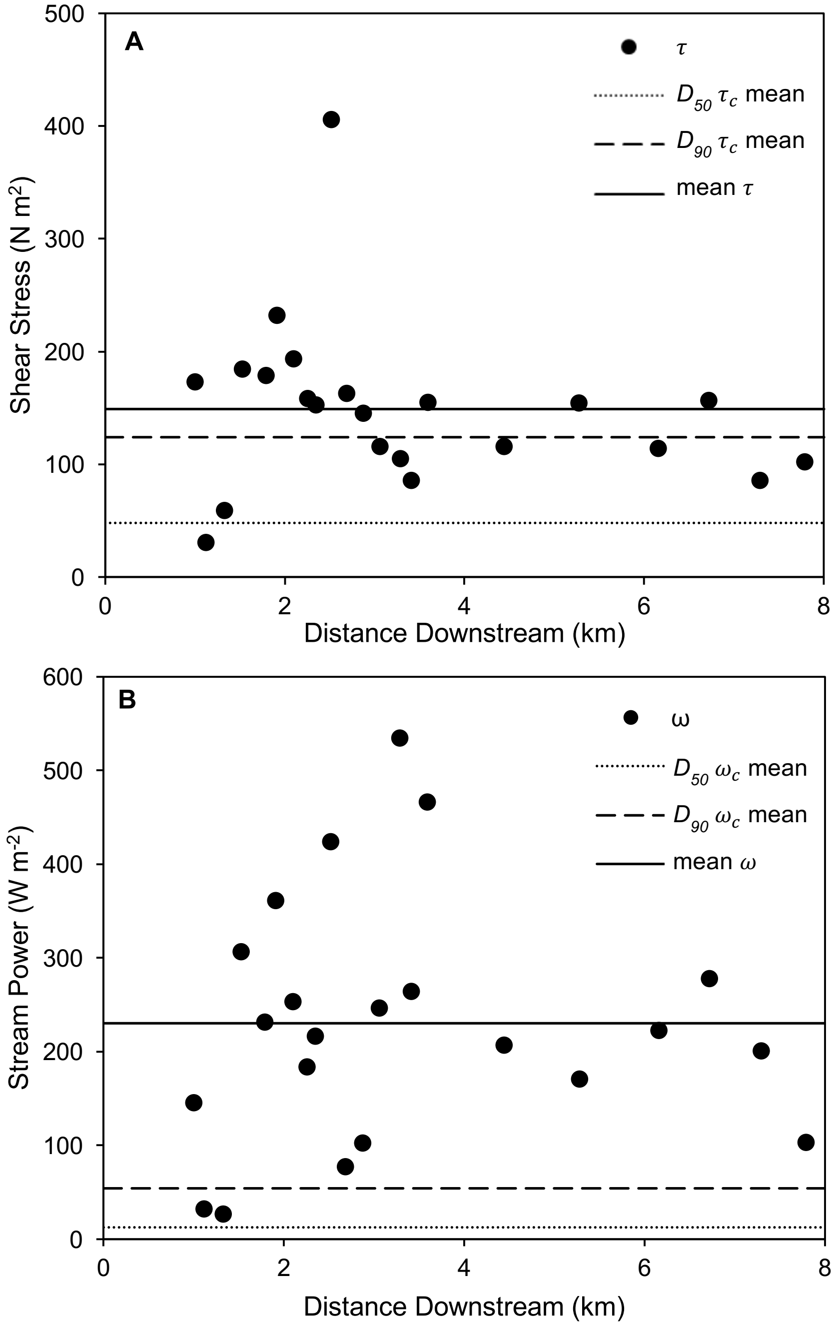


Figure 4.9. Variations in reach averaged shear stress (A) and stream power (B) estimated at the cross section sites for Storm Desmond along St John's Beck.

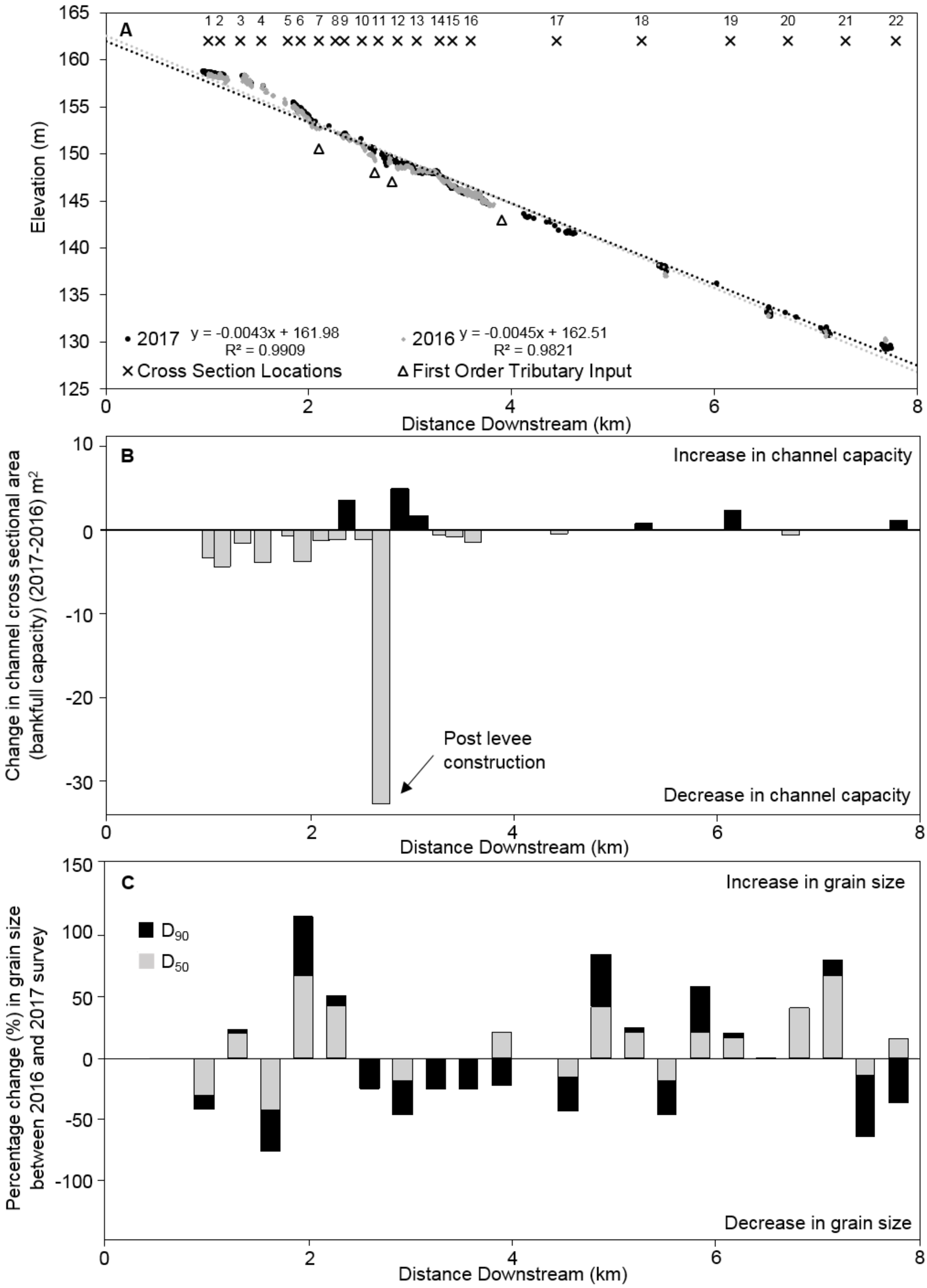


Figure 4.10. Changes in St John's Beck channel long profile, bankfull capacity and grain size between the 2016 and 2017 surveys. (A) Change in bed elevation (long profile), labelled with cross section and first order tributary locations. (B) Change in channel bankfull cross section area. (C) Percentage change in channel bed D_{50} and D_{90} grain size.

4.6.4 Channel resurvey in 2017

Resurveys of St John's Beck longitudinal profile, cross section profiles and grain size in 2017 provide an indication of how the system was recovering 1.5 year after the extreme flood event (Fig. 4.10). There were no significant changes in the mean channel bed slope between the 2016 and 2017 survey, however, there were local changes where there is an increase or decrease in bed elevation height (Fig. 4.10a). Local changes in channel bed elevation result in changes in bankfull channel capacity (Fig. 4.10b). For example, at a distance of 1 to 2.4 km from Thirlmere Reservoir there is a general increase in bed elevation suggesting the deposition of sediment; a pattern further evidenced by a decrease in channel capacity. Overall a decrease in bankfull channel cross-sectional area was observed (at 15 cross sections) 1.5 year after Storm Desmond. Thirteen of these cross-sections are located 1 to 2.7 km downstream from Thirlmere Reservoir (Fig. 4.10b). The largest change and reduction in channel capacity (2.7 km downstream of Thirlmere Reservoir, cross section 11) was 32.8 ± 0.03 m^2 caused by the rebuilding of flood protection levees that reduced channel width to its pre-Storm Desmond size. A total of seven cross-sections displayed either no change or an increase in cross-sectional area and channel capacity. Cross section 9, 2.4 km downstream from Thirlmere Reservoir, showed an increase in channel capacity associated with anthropogenic removal of sediment from the channel bed after the flood event. The percentage change in grain size between the 2016 and 2017 surveys illustrated a general coarsening of bed D_{50} and fining of D_{90} downstream post Storm Desmond (Fig. 4.10c).

4.7 Discussion

4.7.1 Geomorphic impacts of the extreme flood event along the upland sediment cascade

The 2015 Storm Desmond event constitutes the largest recorded event in the available long-term flow and rainfall records for the St John's Beck catchment (Fig. 4.4). The results presented here illustrate the geomorphic work of the flood in terms of sediment erosion and storage along the upper floodplain transfer zone of the USC. The main impacts were associated with erosion of river channel banks and floodplain scour allied with extensive sediment deposition on the floodplains. The summary sediment budget (Fig. 4.11) shows erosion (6500 ± 710 t) was generally balanced by deposition (6300 ±

570 t) along the upper floodplain zone. Less than 6% of the total sediment eroded during the event was transferred out of the reach. Hence, the upper floodplain zone acted as a significant sink for locally-eroded sediment during the extreme event.

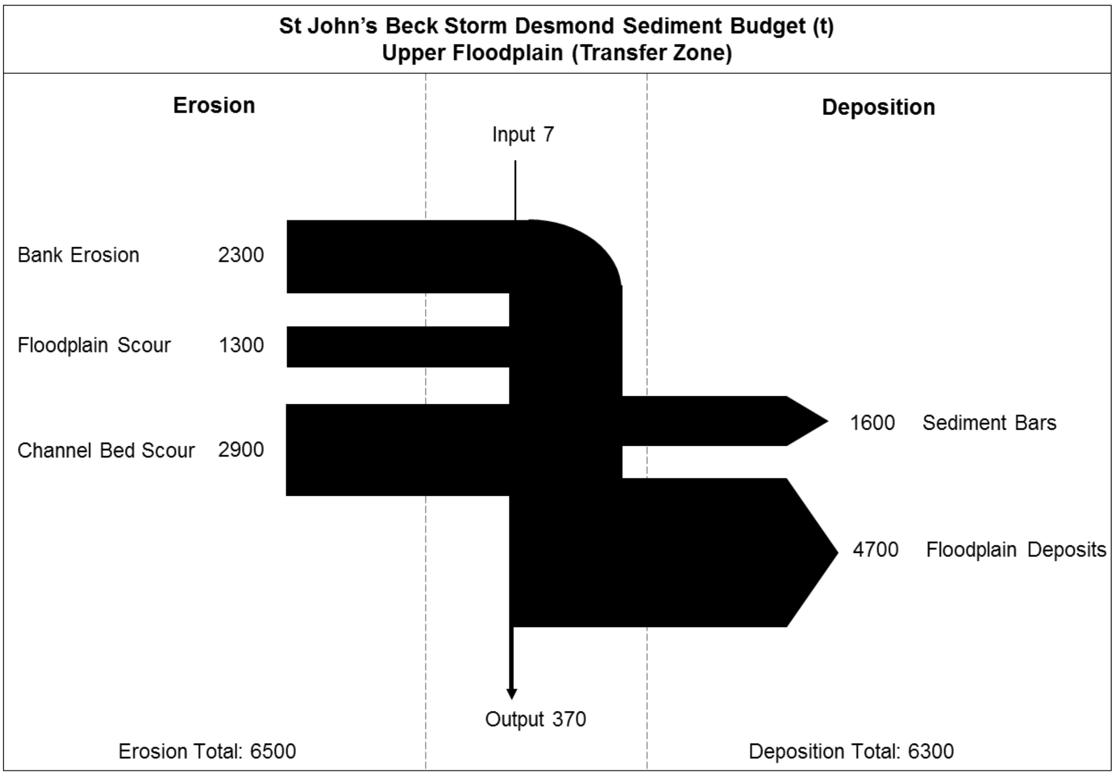


Figure 4.11. Storm Desmond (2015) upper floodplain valley system (transfer zone) mass sediment budget (t) for St John's Beck (effective catchment area 12 km^2).

The geomorphic impacts of Storm Desmond were influenced by the physical characteristics of the upper floodplain transfer zone. Unlike steep headwater catchments dominated by slope-channel linkages and hillslope processes (Harvey, 2001), geomorphic impacts of the event along St John's Beck were controlled by floodplain-channel interactions. Tributaries were only a minor source of sediment as these were disconnected from the channel by sediment traps and therefore are not reported in the sediment budget in Figure 4.11. Sediment was sourced from transient stores, (i.e., channel bars) and through erosion of the channel bed and banks and stored in channel bars and on the surrounding floodplains (Fig. 4.6).

Valley confinement (natural and artificial) controlled the spatial positioning of erosional and depositional storm impacts along St John's Beck (Fig. 4.8). In the upstream reaches

(0 to 1.8 km downstream) the channel was confined by the natural valley topography and geomorphic impacts were comprised of local erosion or sediment bar deposition. Where the natural floodplain valley width increases from 3 to 160 m (1.8 km downstream) and there is an associated decrease in channel slope, rapid floodplain sediment deposition occurred (Fig. 4.6). In contrast, artificially confined reaches (2.7 to 3.6 km downstream) were associated with bank erosion or scour due to local increases in channel bed slope. Major riverbank erosion was observed along an artificially confined reach 2.7 km downstream of Thirlmere Reservoir; here riverbanks were eroded until the channel became unconfined (Fig. 4.8) with extensive floodplain sedimentation. Similar effects have been observed by Magilligan (1985), Nanson (1986), Butler and Malanson (1993), Lecce (1997), Fuller (2007, 2008), who all identified a concentration of erosion on constricted reaches. The transition between confined and unconfined reaches therefore plays an important role in controlling the spatial pattern of erosion and deposition impacts of these events.

4.7.2 Sediment continuity through the upland sediment cascade

The sediment continuity concept focuses on the principle of mass conservation of sediment within a system (Slaymaker, 2003; Hinderer, 2012). The USC has been described as a 'jerky conveyor belt', where sediment can spend a longer time in storage than in transfer (Ferguson, 1981; Walling, 1983; Newson, 1997; Otto et al., 2009). This study has highlighted that sediment continuity is disrupted or 'discontinuous' at the event scale due to storage. Less than 6 % of sediment eroded during Storm Desmond was transported out of St John's Beck (Fig. 4.11). Elsewhere, sediment budget studies have shown similar inefficiencies in sediment transfer, often referring to this as the 'sediment delivery problem' (Trimble, 1983; Walling, 1983; Phillips, 1991; McLean et al., 1999; Fryirs, 2013). For example, in the Coon Creek Basin, USA, less than 7% of sediment left the basin between 1853 and 1977 (Trimble, 1983). In the River Coquet, UK, annual sediment budget within-reach sediment transfer was identified but there was minimal net export of sediment downstream (Fuller et al., 2002). In three UK upland catchments, Warburton (2010) demonstrated sediment transfer is inefficient in the production zone by comparing sediment budgets on an annual, landslide event and flood event timescale. Despite variations in catchment area and the timescale of enquiry, these examples demonstrate there is attenuation of sediment downstream due to storage. This study highlights the importance of the floodplain as a major source and store of sediment at the event scale causing sediment attenuation downstream.

The Storm Desmond event sediment yields were higher than estimated sediment yields for previous flood events along St John's Beck (Table 4.3), indicating the event was significant in generating and transporting large quantities of sediment downstream. The estimated mean shear stress and unit stream power values for Storm Desmond exceeded the thresholds for particle entrainment, indicating sediment on the channel bed was mobilised and transported during the event (Fig. 4.9). Despite this, the event sediment yield is lower than the total quantity of sediment eroded. Sediment transfer during extreme events, where overbank flows are produced, is reduced on the floodplains (because of variations in roughness, slope, local topography) compared to the channel, resulting in sediment deposition (Trimble, 1983; Moore and Newson, 1986). Consequently, sediment continuity through the upper floodplain transfer zone during extreme events will ultimately be controlled by the conveyance of sediment across floodplains, and the propensity for sediment deposition during overbank flows. Future flood events may promote exchanges in sediment stores and movement of sediment downstream in pulses or waves, thereby influencing sediment yield (Nicholas et al., 1995). However, if a future similar magnitude event were to occur along St John's Beck, it is likely that the reach sediment output would again be lower than the total sediment eroded along the river corridor due to deposition on the floodplains.

Previous studies have described the potential linkages between sources and stores of sediment in terms of connectivity or disconnectivity (Hooke, 2003; Fryirs, 2013; Bracken et al., 2015). However, few of these studies have quantified the mass exchange of sediment between different landscape units during flood events (Thompson et al., 2016) and assessed their impact on sediment yield. This study is among the first to effectively quantify sediment attenuation in the upper floodplain zone of the USC during an extreme event.

4.7.3 System recovery

Fluvial systems can take decades (Wolman and Gerson, 1978; Sloan et al., 2001) to millennia (Lancaster and Casebeer, 2007) to recover from extreme events, with some systems never fully recovering to the pre-flood condition. The channel re-survey one year after Storm Desmond showed that 70 % of cross sections had a reduced channel capacity reflecting sediment aggradation in the channel (Fig. 4.10). A reconnaissance survey prior to Storm Desmond identified distinct reaches of sediment aggradation in the system (in particular, 2 to 2.5 km downstream of Thirlmere Reservoir), suggesting the river is displaying characteristics similar to the pre-flood system. Long term flow regulation and upstream sediment trapping by Thirlmere Reservoir has influenced sediment continuity, implying that the sediment regime is already disturbed by the legacy of anthropogenic modification (Wohl, 2015). Phillips (1991) states that stores of sediment may develop in fluvial systems so the system can maintain sediment yields when sediment from upstream is reduced. The critical shear stress and critical stream power entrainment thresholds for channel bed particle D_{90} estimated using the 2017 survey data were not exceeded during daily flows after storm Desmond indicting coarse sediment immobility. It is likely that the finer material was transported in 2017 and deposited downstream in aggradational zones where channel dimensions change (i.e., reduction in slope, width and depth), resulting in further aggradation downstream and apparent coarsening in reaches where the fine sediment was partially mobilised. Therefore, local aggradation observed could be a response to long-term system disturbance and transport-limited flows.

The most significant changes observed along St John's Beck one year after the flood were associated with anthropogenic modifications to the system through the rebuilding of flood protection levees, reinforced river banks and removal of sediment from the channel bed and floodplains (2 to 4 km downstream); these modifications took place after the 2016 field campaign. Distal floodplain deposits were located 70 m from the channel and therefore can only be remobilised during overbank flows with similar peak discharges where the critical entrainment thresholds are exceeded. Consequently, system recovery and sediment transfer depends on the conveyance capacity of the valley floodplains in addition to the stream channel capacity (Trimble, 2010). If sediment was not anthropogenically removed from the floodplains, it would have a long residence time in this store and only be remobilised during overbank extreme flows at least as powerful as

Storm Desmond. Flood levees were rebuilt 2.7 km downstream to the pre-flood position, it is likely that if these levees were not restored the river would permanently occupy the post-Storm Desmond position; a natural 're-wilding' process (Fryirs and Brierley, 2016).

Review of available historic maps and air photographs of St John's Beck over the last 150 years (1860s – 2010), indicated that there has been relative 2D lateral planform stability despite the occurrence of high magnitude flood events (Table 4.1). This is because during extreme events, such as Storm Desmond, there is relative sediment continuity due to floodplain storage, and evidence of flood events is often quickly cleared.

4.8 Chapter conclusions

This Chapter has quantified the planform adjustment response of an upper floodplain river system (transfer zone) to an extreme high magnitude flood event: Storm Desmond, 2015. Based on these results, the primary conclusions of this work are:

1. Sediment continuity through the upper floodplain transfer zone was highly disrupted during Storm Desmond, with less than 6 % of the eroded sediment being transported out of the system.
2. Floodplains acted as a major sink of coarse sediment during the flood, storing 72 % of the eroded sediment, although these floodplains can also be a source of sediment through scouring and erosion processes.
3. Spatial patterns of erosion and deposition were controlled by valley confinement; where the channel is naturally unconfined overbank floodplain deposits were prominent, in contrast, in artificially-confined reaches, bank erosion and scour were dominant geomorphic impacts.
4. The event exceeded critical entrainment thresholds for channel bed particle D_{50} and D_{90} transporting sediment that had aggraded in the channel. Critical entrainment thresholds were not exceeded during daily flows for all particle sizes along St John's Beck in the 2017 survey.
5. Channel capacity decreased 1.5 year after the event and channel bed grain size had coarsened due to aggradation in the channel.

This Chapter has quantified the importance of the upper floodplain valley transfer zone in regulating sediment output during extreme flood events. The results suggest that rather than envisioning upper floodplain zones as effective transfer reaches they are actually major sediment storage zones that capture flood sediments and disrupt sediment continuity downstream. The intervening valley floodplain geomorphology (confinement, slope) plays a major role in influencing the spatial location of erosion and deposition impacts. This Chapter has highlighted the importance of the extreme flood event in influencing sediment continuity and planform adjustment at the reach scale. However, a key question remains: are extreme events the main driver of planform adjustment at the regional scale over the past 150 years?

Chapter 5 and 6 will explore sediment continuity by investigating lateral 2D planform adjustments across 17 catchments in the Lake District upland study region over 150 years. The 2D approach means vertical changes in river channel adjustment are not captured and a full 3D analysis of morphological change is not possible (see Chapter 4). Nevertheless, a 2D approach has the important advantage that a wider spatial (full catchment), and longer historical assessment (150 years) of sediment continuity can be captured.

Chapter 5

A catchment scale assessment of the patterns and controls of historic 2D river planform adjustment

Published paper:

Joyce, H.M., Warburton, J., Hardy, R.J., (2020). A catchment scale assessment of patterns and controls of historic 2D river planform adjustment. Geomorphology https://doi.org/10.1016/j.geomorph.2020.107046

5.1 Chapter summary

The supply, transfer and deposition of sediment from channel headwaters to lowland sinks, is a fundamental process governing upland catchment geomorphology, and can begin to be understood by quantifying 2D river planform adjustments over time. This chapter develops a catchment scale methodology to quantify historic patterns of 2D channel planform adjustment and considers geomorphic controls on 2D river stability. The methodology is applied to 18 rivers (total length = 24 km) in the upland headwaters of the previously glaciated Wasdale catchment (45 km^2), in the Lake District study region. Planform adjustments were mapped from historic maps and air photographs over six contiguous time windows covering the last 150 years. A total of 1048 adjustment and stable reaches were mapped. Over the full period of analysis (1860 – 2010) 32% (8 km) of the channels studied were adjusting. Contrasts were identified between the geomorphic characteristics (slope, catchment area, unit specific stream power, channel width and valley bottom width) of adjusting and stable reaches. The majority of adjustments mapped were observed in third and fourth order channels in the floodplain valley transfer

zone, where the channels were laterally unconfined (mean valley bottom widths of 230 ± 180 m), with low sediment continuity. In contrast, lower order channels were typically confined (mean valley bottom widths of 31 ± 43 m) and showed relative 2D lateral stability. Hence, valley bottom width was found to be important in determining the available space for rivers to adjust. Over the full period of analysis 38% of planform adjustments involved combined processes, for example, as bar and bend adjustments. The study demonstrates the importance of stream network hierarchy in determining spatial patterns of historic planform adjustments at the catchment scale. The methodology developed provides a quantitative assessment that can be applied to multiple catchments in a region (Chapter 6).

5.2 Introduction

To understand the spatial and temporal pattern of planform adjustments and sediment continuity it is important to quantify the types of planform adjustments and variables controlling planform stability, spatially and temporally (Martínez-Fernández et al., 2019). Two-dimensional planform adjustments can be readily identified from historic maps and air photographs over the last century (the period of measurable change) when such resources are available. This provides a suitable time span to understand planform adjustments in response to recent changes in climate and land use (Schumm and Lichty, 1965; Hooke and Redmond, 1989b; Winterbottom, 2000; Higgitt et al., 2001). However, there is no consistent quantitative methodology that applies a catchment wide assessment of the temporal patterns of planform adjustment from channel headwaters to lowland sediment sinks (Bizzi et al., 2019).

This Chapter presents a catchment-wide methodology to quantitatively assess the patterns and geomorphic variables of historic 2D river planform adjustments within a sediment continuity framework. The specific objectives of the methodology are: (i) to quantify the spatial pattern of channel planform adjustment over the era of measurable change (last 150 years), (ii) quantify the geomorphic variables forcing channel planform adjustments, and (iii) use data from (i) and (ii) to understand spatial and temporal patterns of channel planform adjustments at the catchment scale. The method is applied and tested in the Wasdale catchment in the Lake District study region (Chapter 3). This catchment is selected because it exhibits a rich variety of fluvial forms including: bedrock, confined, unconfined wandering and braided channels (Harvey, 1997), and has available historic maps and air photographs covering the last *c.* 150 years.

5.3 Methodology

The methodology proposed here quantifies 2D historic channel planform dynamics in upland catchments. The method is structured on Strahler's (1952; 1957) stream order to reflect the natural scaling of geomorphic variables: catchment area, channel width, length, slope, stream power and valley bottom width (Leopold and Miller, 1956; Strahler, 1957; Miller et al., 2003; Hughes et al., 2011). The approach is applied at the catchment scale and comparisons are made between stream orders in a similar regional setting. The method uses commonly available datasets, including: digital terrain models (DTM), air photos, historic topographic maps, bedrock and superficial geology data, which are analysed in a Geographical Information System (GIS) package (Fig. 5.1). These data requirements allow 2D patterns of river planform adjustment to be identified, and 1D and 2D catchment geomorphic variables to be extracted. The workflow is summarised in Fig. 5.1 and involves three main parts:

Part 1. Pre-processing:

a) Assembly and geo-referencing of available data (DTM, historic maps, air photographs, geology data).
b) Identification of catchment, delineation of the channel network, stream order network and the rivers to be studied.

Part 2. Characterisation of fluvial system and assessment of planform evolution:

a) Identification, extraction and calculation of at-a-point geomorphic characteristics including: channel slope, valley bottom width, channel width, stream power, catchment area, bedrock and superficial geology.
b) Identification and classification of channel planform adjustment types and stable reaches over time.

Part 3. Analysis: linking planform adjustments to at-a-point geomorphic characteristics to understand the controls influencing the spatial and temporal pattern of planform adjustment.

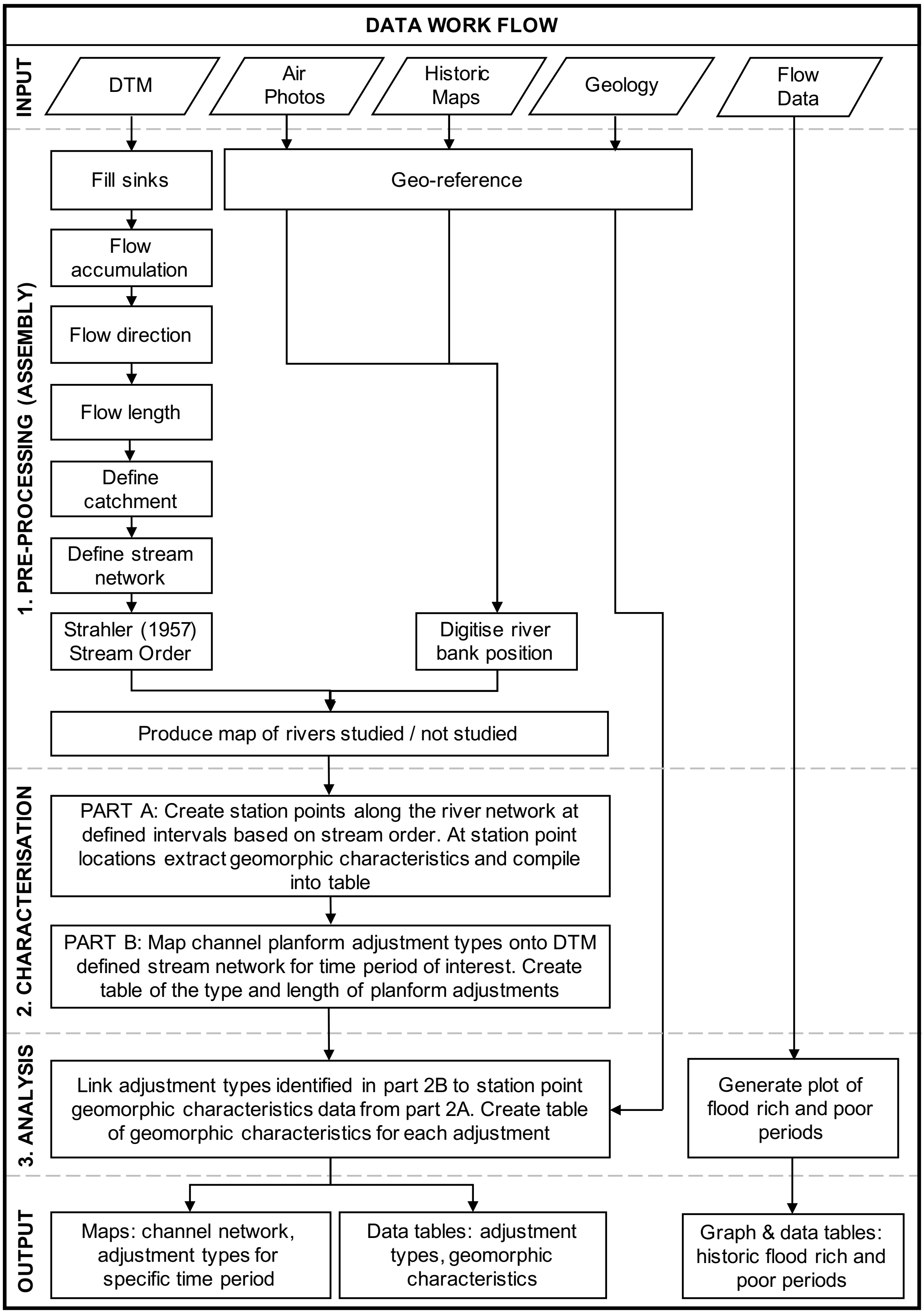


Figure 5.1. Data requirements and GIS workflow for identifying and analysing planform adjustments, stable reaches and geomorphic variables. Part 1 involves manipulation of the DTM using GIS hydrology tools to identify the rivers and catchment typology. Part 2 involves identifying planform adjustments and extracting at-a-point channel and catchment geomorphic variables. Part 3 involves linking parts 2A and 2B together. Part 2B and 3 are repeated for the different time periods of available historic maps and air photographs.

5.3.1 Part 1: Pre-processing - assembly of data and identification of spatial scales

The methodology takes a top-down perspective working down the sediment cascade from upland channel headwaters to a point where the river channel enters either a major lowland valley waterbody (lake) or, if no water body is present, an endpoint is defined at a point in the lowland valley. In UK upland regions, the lowland valley is commonly defined where the river channel network is no longer surrounded by hillslopes above 300 m elevation (Atherden, 1992).

The catchment, river channel network and Strahler (1952, 1957) stream order are first defined using a high-resolution DTM and automated flow delineation tools in GIS. The stream order network provides a stratified framework in which the spatial location, length and type of planform adjustments observed between the temporal data (historic maps/air photographs) are mapped (Part 2B).

The time interval and frequency over which 2D planform adjustments can be identified depends on the availability of data. In the UK, studies of channel planform adjustments can, in some cases, be identified from sources dating from the sixteenth century to present (Lewin, 1987; Macklin and Lewin, 1989; Petts et al., 1989; Macklin et al., 1992; Downward et al., 1994; Milton et al., 1995; Winterbottom, 2000), (Table 5.1). Early sources (1600-1840s) (e.g., estate maps, deposited plans, enclosure and tithe maps) have limited spatial coverage and accuracy, therefore they are not always suitable for assessing river planform adjustments at the catchment scale (Ferguson, 1977). The earliest maps with full continuous spatial coverage suitable for identifying planform adjustments at the catchment scale across England and Wales are the Ordnance Survey (OS) County Series maps (after 1840s) at a scale of 1:10,560 (Harley, 1975; Downward et al*.,* 1994). Subsequent National Grid series and National Grid imperial and metric map editions (scale range 1:10,560 - 1:10,000), produced from large scale air photographs, provide a full coverage of England and Wales from the 1940s – 1990s (Table 5.1). Catchment and regional scale air photographs provide a recent (1940s - present) view of channel planform at a high resolution (i.e., 0.25 m) (Werritty and Ferguson, 1980; Petts et al., 1989). Air photographs and historic maps are geo-referenced in GIS for planimetric accuracy, following previous recommendations, using >8 hard-edged ground control points (GCPs) and a second order polynomial transformation (Hughes et al., 2006; Donovan et al., 2015;

Donovan et al., 2019). Although scale differences and geo-referencing errors will exist between historic maps and air photographs, the datasets provide a valuable record of catchment scale 2D planform over a period of measurable change of approximately the last 150 years.

Table 5.1. Details of historical maps and air photographs available for the UK (modified from Hooke and Redmond, 1989b).

	Date	Map Source	Scale	Coverage of UK	Reference
	Late 16th Century, majority <1700	Estate	Usually 1:2376	Over 20,000 available for consultation in England	Harley (1972)
	18th and 19th Century	Enclosure		Variable in England and Wales	Tate (1978)
	1840s	Tithe	Usually 1:2376 or 1:4752	3/4 of England and Wales	Kain and Prince (1985)
	Post 1794	Deposited plans	Min. scale 1:15,840 after 1807	Britain	Harley (1972)
	18th and 19th Century	County	1:63,360; 1:31,689	England and Wales	Skelton (1970); Rodger (1972)
	1747 - 1755	Military Survey of Scotland (Roy)	1:36,000	Scotland	Moir (1973)
	1795 - 1755	Ordnance Survey Old series 1st ed.	1:63,360	England and Wales	Harley (1965)
	1840 - 1926	Ordnance Survey New Series 2nd – 4th ed.	1:63,360	England and Wales	Harley (1965)
◆	1854 - 1949	County Series 1st ed. – 3rd revision	1:2,500; 1:10,560	England and Wales	Harley (1965)
◆	1943 - 1992	National Grid Series Edition A - E	1:1,250, 1:2,500	England and Wales	Harley (1975)
	1948 - 1982	National Grid Imperial 1st Edition. (1st – 3rd Revision)	1:10 560	England and Wales	
◆	1969 - 1996	National Grid 1:10,000 series, fully metric, 1st edition	1:10,000	England and Wales	
	1958 - 1996	National Grid 1:10,000 metric and 1:10,560 imperial latest editions	1:10,560 and 1:10,000	UK	
◆	1960s - present	Air photographs	1:250 - 1:200,000	High – covers England and Wales – composite of images	

◆ sources of data used in the Wasdale case study

5.3.2 Part 2: Characterisation of fluvial system and assessment of planform change

Channel planform adjustments and geomorphic variables are measured in two parts. Part 2A involves extracting geomorphic channel and catchment variables at station points (SP) located along the river channel network. SPs are located at intervals scaled according to the stream order to reflect the natural scaling of channel width, valley bottom width, bar size, channel length and catchment area downstream (Leopold and Maddock, 1953; Strahler, 1957; Miller et al., 2003; Hughes et al., 2011). The SP spacing interval is shorter for low stream orders, compared to high stream orders to account for the differences in channel size across a catchment. This approach differs to previous studies that have averaged river variables over length, or extracted geomorphic variables at a fixed spacing interval and applied this to the entire channel network (Fryirs et al., 2009; Lisenby and Fryirs, 2016) (Figure 2a). A fixed interval spacing can result in an unrepresentative sample where short, low stream order channels have only one SP to extract geomorphic variables, compared to longer higher stream order channels (Fig. 5.2).

The stream order channel network is transferred into an acyclic graph (river graph) (Heckmann et al., 2015; Schmitt et al., 2016), which represents the network topology with a series of nodes (Fig. 5.2). Nodes are located at the start and end (tributary junction, or waterbody) of each channel (Fig. 5.2). For each stream order, the first SP is located at the start node of the river. A point is then located at a user-defined distance (SP interval) downstream from the first point (e.g. 100 m); the next point is located at the stream order SP interval distance downstream from the last point and the pattern continues downstream. Where the distance from one SP to the last SP is less than the point spacing sampling increment, the measurement point is selected on the channel of interest upstream (i.e. of a junction or lake) where there are no significant lake or tributary backwater effects (Richards, 1982; Hey, 1979).

To select an appropriate SP interval, different spacing intervals can be tested. Assuming a minimum of two SPs on the shortest channel, a low-resolution SP spacing interval will have a long spacing interval (for example, 400 m for second order channels, 1000 m for fifth order channels). In contrast, a high-resolution SP interval will have a short spacing interval (for example, 100 m for second order channels, 400 m for fifth order channels). Geomorphic characteristics can be extracted from the different SP intervals at different resolutions and analysis of covariance, ANOCOVA (Zar, 2010) can be used to identify statistical differences between the geomorphic variables of the different SP interval resolutions. If no statistical differences are present, the lowest resolution SP interval can be used to represent system geomorphic characteristics. Station point interval spacing could also be based on hydraulic geometry laws (e.g. a function of channel width (Leopold and Miller 1956), or based on variability in grain size or sediment flux (Schmitt et al., 2016; Tangi et al., 2019). For example, the CASCADE modelling framework (Schmitt et al., 2016; Tangi et al., 2019) converts the river network into a series of reaches and nodes (river graph), which is expanded to represent attributes such as grain size or sediment flux to each reach (between two nodes). Each reach is then assigned a transport capacity to identify sediment flux and sinks of sediment. This research characterises observed patterns and types of adjustment, as a result a modelling approach was not adopted.

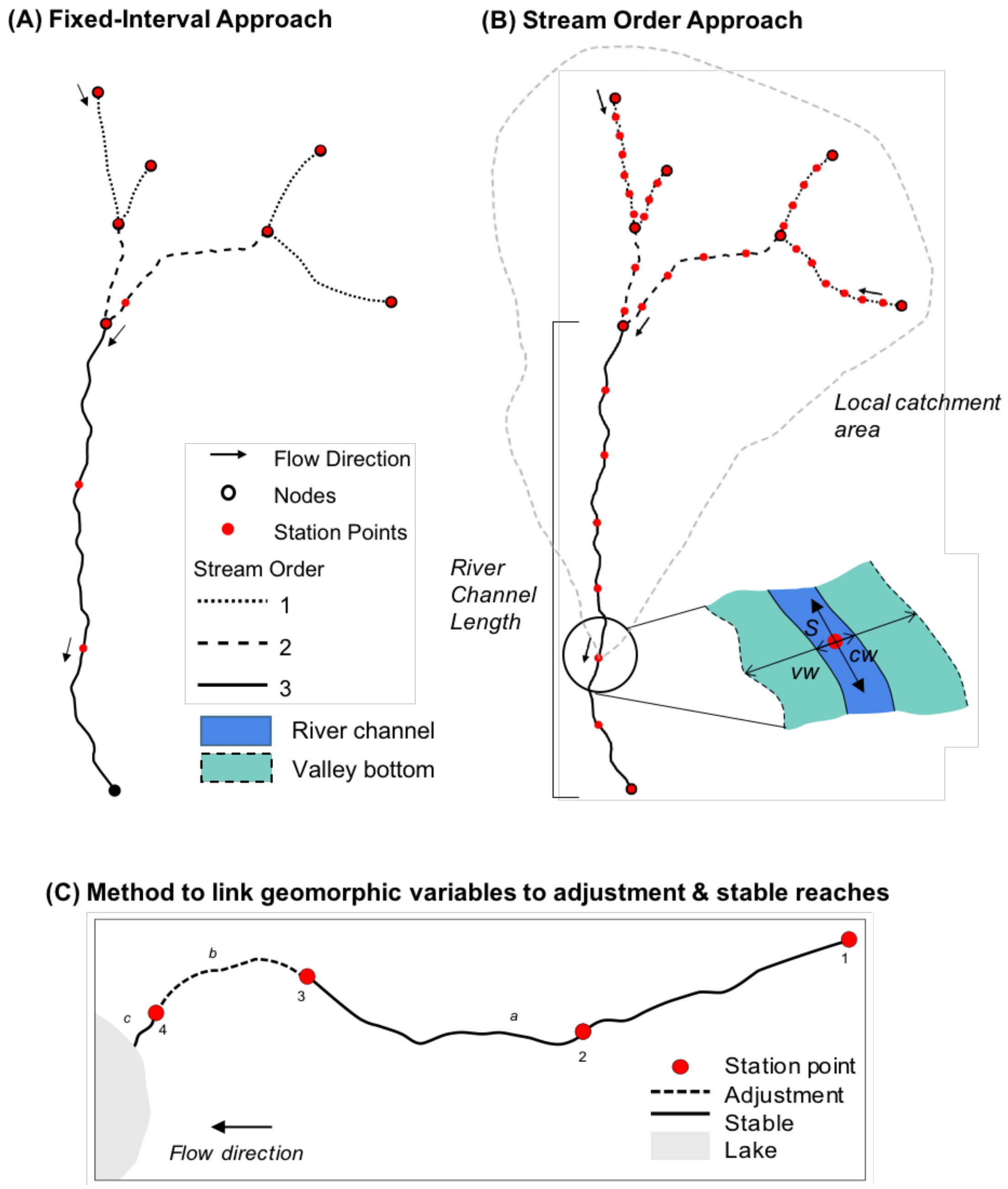


Figure 5.2. Schematic of stream order channel start and end nodes and station point spacing intervals. A) Example of 'fixed interval approach', a fixed station point interval distance often used on high order channels, applied to each stream order. This approach results in low order channels having 1 SP at the start node of the channel network (first and second order channels). B) Example of SP intervals adjusted for each channel stream order and diagram of how geomorphic variables (vw = valley bottom width, cw = channel width, S = slope) are extracted in the methodology developed in this Chapter. C) Diagram showing how SP variables are related to planform adjustments. Continuous lines represent stable reaches (*a*, *c*), dashed lines indicate planform adjustments (*b*). Red dots indicate the station points and the number indicates the station point ID.

At each SP, the channel and catchment geomorphic variables (Table 5.2), are extracted and compiled into an attribute table (Fig. 5.1). These variables provide insight into reach and catchment scale morphology and sediment morphodynamics and can be directly extracted from the DTM or historic maps and air photographs (Martínez-Fernández et al., 2019; Bizzi et al., 2019). The key variables are defined as follows:

Channel length (m) is measured from the start of the stream order or junction node to the corresponding downstream end or junction node and represents the total channel length of the stream in that order (Fig. 5.2b). *Local channel slope (-)* is calculated at each SP. Elevation values are extracted from the DTM at intervals upstream and downstream of the SP that scale with each stream order (e.g., (stream order number – 1)*100)) to account for the variability in channel scale between the stream orders. *Local valley bottom width (m)* is measured at each SP, perpendicular to the channel banks and identified by breaks in slope along the distal edges of floodplains and terraces from a slope map created from the DTM in GIS (Snyder and Kammer, 2008; Fryirs and Brierley 2010). It defines the potential extent to which a channel can freely migrate laterally across the floodplain and therefore can define confined and unconfined channels (O'Brien et al., 2019). *Channel width* (m) is defined as the active channel width including bars and is measured at each SP perpendicularly from bank to bank (Wishart, 2004). *Bedrock* and *superficial geology* are categorical variables and are assigned locally to the observed river planform adjustments and stable reaches in part 3 of the method. *Local catchment area (km^2)* is defined as the upstream contributing area of a SP based on the surface topography from the DTM (Fig. 5.2b).

Based on the measured geomorphic variables secondary data can be calculated. For example, local catchment area is used to estimate discharge using a discharge-area power relationship (Knighton, 1999):

$$Q = a \cdot A^b \quad (1)$$

where, A is the catchment area (km^2), and a and b are empirical coefficients derived from a power function fitted to area-discharge data. Many headwater catchments are ungauged, however discharge data from multiple gauging stations in a study region can be used to generate a regional catchment area-discharge relationship. For each gauging station within the study area flow return periods are calculated and plotted against their respective catchment areas to calculate regional a and b coefficients.

Unit specific stream power (W m^{-2}) indicates river energy expenditure and the potential for sediment transfer and channel planform adjustment (Bagnold, 1966; Baker and Costa, 1987; Thompson and Croke, 2013; Marchi et al., 2016; Martínez-Fernández et al., 2019). Specific stream power is calculated using channel width and an area-discharge relationship (Eq. 1) for a region or catchment (Bagnold, 1966; Baker and Costa, 1987):

$$\omega = \frac{\rho g Q S}{w} \quad (2)$$

where ω is the unit stream power (W m^{-2}), ρ is the density of water (kg m^{-3}), g is the acceleration of gravity (m s^{-2}), Q is the discharge (m^3 s^{-1}), S is channel bed slope (-) and w is the channel width (m). Here, a return interval of 2 years is used for Q and ω calculations, which reflects the discharge that approximates bankfull conditions (Leopold and Wolman, 1957; Dury, 1961; Hey, 1975) and the potential for geomorphic work (Lisenby and Fryirs, 2016; Marchi et al., 2016).

Flood events prior to instrumental records can be identified from the analysis of historical documents (newspapers, reports etc.). In the UK, the Chronology of British Hydrological Events (www.cbhe.hydrology.org.uk) provides a database of historical precipitation and flood events before 1937 (Black and Law, 2004). Using historic and gauged flow data the cumulative number of flood events, following methodology of Pattison and Lane (2012), can be used to identify flood-rich and flood-poor periods and link to the timing and frequency of historic river planform adjustments.

Part 2B identifies the type of 2D planform adjustment along the river network over a given time interval. The type of adjustment (Fig. 5.3) is mapped as a polyline feature from the start to the end of the adjustment so that its location can be related to SP geomorphic variables and the length of the planform adjustment quantified. Reaches with no observed 2D planform adjustment are mapped as 2D stable indicating a balance of sediment input and output. However, it is important to note that these rivers might be adjusting vertically, which cannot be quantified in 2D analyses of historic maps and air photographs.

Table 5.2. Example of 1D and 2D geomorphic variables that can be extracted from historic maps, air photographs, geology maps and DTMs at different spatial scales, and the key processes they indicate (modified from Gurnell et al., 2015).

Spatial Unit	Key Process	Data Variable
Region	Water balance Sediment production Topographic conditioning (i.e. presence of mountains, lakes)	Climate data (precipitation (mm), discharge (m^3 s^{-1}) Geology Topography derived from DTM
Catchment	Runoff production / retention Sediment production Topographic conditioning (i.e. presence of mountains, lakes)	Climate data (precipitation (mm), discharge (m^3 s^{-1}) Geology Topography derived from DTM
River	Channel network structure Flow & sediment regime (supply, transfer and deposition)	Stream order and channel dimensions: catchment area (km^2), Length (km), river channel slope (-) Discharge (m^3 s^{-1}), geology
Reach	Planform adjustments (sediment regime)	2D Planform adjustments identified from historical datasets Local slope (-), discharge (m^3 s^{-1}), channel width (m), unit (specific) stream power (W m^{-2})
Geomorphic Unit	Sediment regime	2D adjustments to channel bars (i.e. bar area reduction, reorganisation or accretion) identified from historical data sets

Figure 5.3 demonstrates the types of channel planform adjustments identified in alluvial rivers (Hooke, 1977; Schumm, 1985; Fryirs et al., 2009; Lisenby and Fryirs, 2016). Planform adjustments are divided into four categories based on the characteristic scale of each adjustment. The four categories are not mutually exclusive and some adjustments may occur in combination, for example, bend adjustments are associated with the erosion

of the outer riverbank and subsequent sediment deposition on the inside bend forming channel bars (Hickin, 1978; Richards, 1982).

Boundary adjustments are associated with an alteration to the channel planform where the channel: avulses across the floodplain, generating a new, secondary or multiple flow paths (Allen, 1965; Nanson and Knighton,1996; Slingerland and Smith, 2004), switches from multiple flow paths to a single flow path (Passmore et al., 1993), or is shortened via cut offs causing channel straightening/realignment. Boundary adjustments can take place at the reach scale (i.e., cut off), or affect the entire channel length (i.e., avulsion) (Slingerland and Smith, 2004). They typically occur over a short time period (<1 yr), often during a flood event (Jones and Schumm, 1999), although they can also be progressive, occurring in response to continued erosion and deposition of sediment (Stouthamer and Berendsen, 2001).

In contrast, channel width adjustments affect shorter lengths of river channel. Here, width adjustments are defined where there is a major change (>50%) in the channel width to avoid misrepresentation of minor width adjustments caused by image scale-related effects. Bend adjustments can occur via extension, expansion, translation enlargement, rotation or complex change (Hooke, 1977; Fryirs et al., 2009) (Fig. 5.3). Bend and width adjustments can be progressive adjustments or occur in response to a flood event. The development of bars in the channel can cause width, bend or boundary adjustments or can be a response to these adjustments (Fig. 5.3) (Leopold and Wolman, 1957). The pattern and rate of bar adjustments can be a useful indicator of the stability of river channels (Church and Jones, 1982). Bar adjustments can occur over short temporal scales, in response to an event (i.e., flood, valley landslide) or be present in the channel for ~100 year (Jackson, 1975; Church and Rice, 2009). Bar adjustments are considered to be more stable forms of adjustment inherent within the system when they occur singularly (e.g., not in combination with another adjustment), compared to boundary or major width adjustments that involve a change to the position and 2D form of the channel on the valley floor (Brierley and Fryirs, 2005b; Fryirs and Brierley, 2012).

The transformation of the entire channel from one planform type to another, for example straight planform to braided, is often termed channel metamorphosis and represents a change in the sediment and/or flow regime (Schumm, 1979). Channel metamorphosis can be temporary, for example, a straight channel can become braided due to deposition of sediment and then switch back to a straight channel (Warburton et al., 1993); or permanent, for example a transition from a single thread to a braided system (Harvey, 1991). Avulsions can lead to river metamorphosis (Schumm, 1977). Identifying the types of planform adjustment is important for inferring patterns of sediment continuity through the USC.

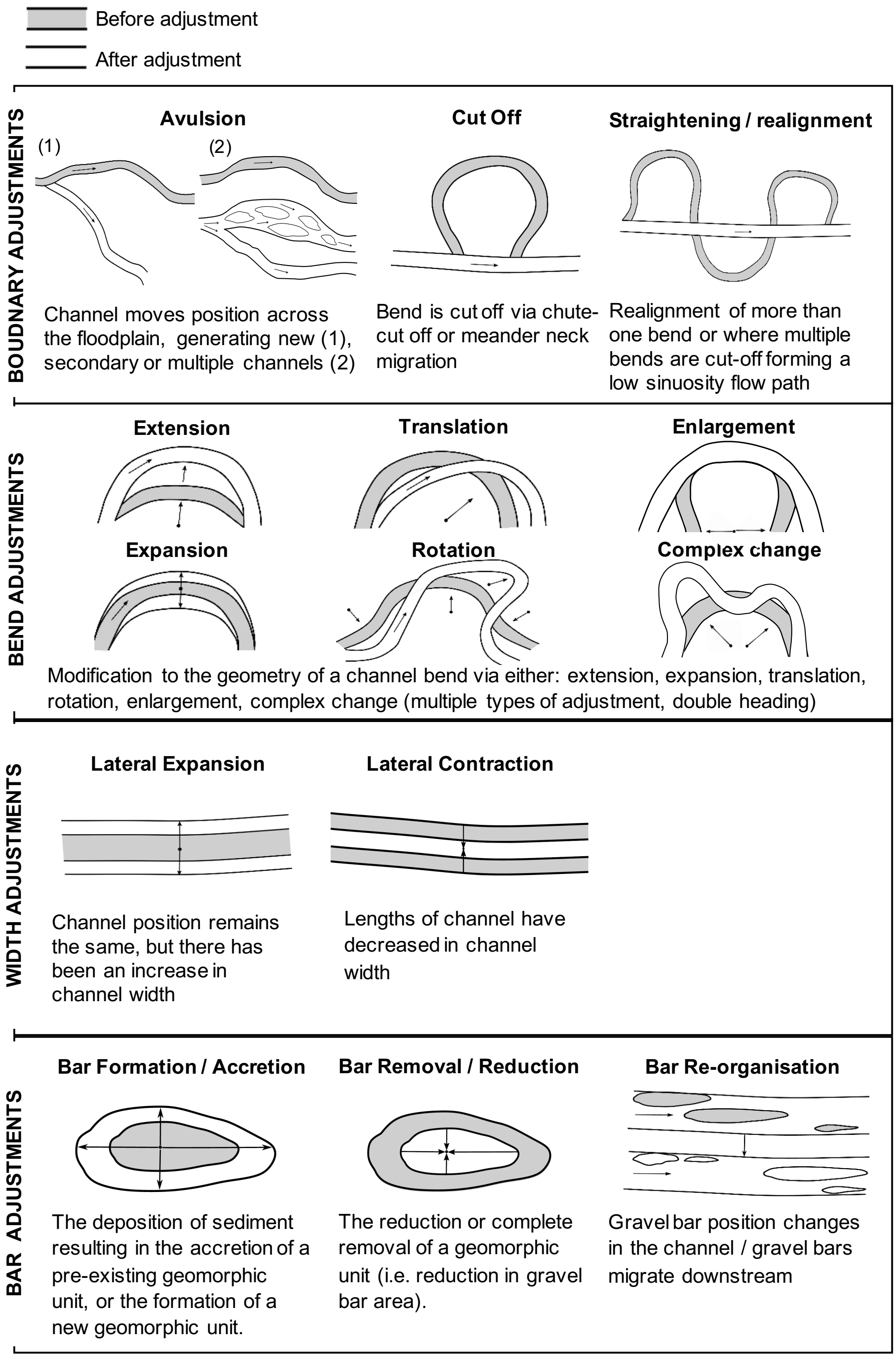


Figure 5.3. Schematic of planform adjustment types and definitions adapted from Brierley and Fryirs (2005) and Fryirs et al., (2009).

The types of 2D planform adjustment outlined in Figure 5.3 are readily identified by comparing historic maps and air photographs. Therefore, geo-referencing errors between historic maps and air photographs are unlikely to significantly affect the categorisation of the adjustment type or adjustment length.

5.3.3 Part 3: Analysis of planform adjustments and geomorphic variables

The main outputs of Part 2 include: (A) channel and catchment geomorphic variables at station points along the channel network, and (B) 2D channel planform adjustment types and stability as polyline features along the channel network for each time period. Part 3 combines parts 2A and 2B to develop an understanding of the key geomorphic variables influencing the types of planform adjustment and stability.

To link SP variables to adjustment and stable reaches there are two approaches, Method 1 (M1) and Method 2 (M2). M1 involves averaging the geomorphic variables of the SP upstream and downstream of the planform adjustment or stable reach. For example, in Figure 5.2c adjustment *b* is assigned the mean geomorphic variables of SP 3 and 4. In M1, if an adjustment or stable reach extends or lies between two or more SP then the average geomorphic variables are taken from all of the respective SP (Fig. 5.2c). If an adjustment extends over the junction between two stream orders (i.e. at tributary junctions) the mean geomorphic characteristic variables are taken from the upstream SP and downstream SP. If the adjustment occurs downstream of the last SP (i.e. upstream of a lake or waterbody) it is assigned the variables of the last closest SP.

An alternative approach, M2, involves automatically assigning adjustment and stable reaches the closest SP variables in GIS. However, M2 only assigns the adjustment to the closest SP and therefore does not characterise the full range of geomorphic values an adjustment might occur over. In addition, M2 requires careful checking as SPs can be incorrectly assigned to adjustments from close proximity SPs on neighbouring channels. This is particularly problematic near tributary junctions when there is a high density of SPs for multiple channels. In this respect, M1 is chosen and therefore used for the rest of the analysis.

5.4 Case Study

5.4.1 Part 1: Selection of region, assembly and pre-processing of data

To test this approach, the methodology is applied to the Wasdale Catchment (45 km^2, Fig. 5.4) in the Lake District, north-west England. This upland catchment is strongly influenced by the geology, glacial history and climate with a dynamic fluvial system (Harvey, 1997). The present river planform consists of straight low sinuosity first and second order erosional bedrock channels, e.g., Piers Gill and Gable Beck (Fig. 5.4). Downstream, depositional features dominate, and channels are unconfined with wandering and braided planforms in the third, fourth and fifth stream orders (Fig. 5.4C) (Harvey, 1997). A small debris cone is present where Gable Beck joins Lingmell Beck and there is a large fan delta where Mosedale and Lingmell Becks empty into the head of Wast Water, which adjoins an alluvial fan of Lingmell Gill (Harvey, 1997).

The bedrock geology of the area consists of Ordovician Borrowdale Volcanic Group rocks (Wilson, 2005). The superficial geology consists of primarily fluvial deposits in the lower reaches of Mosedale Beck, Lingmell Beck and Lingmell Gill (Fig. 5.4C). Glacigenic deposits (Devensian till, diamicton) are found in the upper reaches and headwaters of the river channels (Fig. 5.4). River channel sediments are generally coarse, typically boulder gravels in the upper reaches fining to cobble gravels downstream (Skinner and Haycock, 2004). Little evidence of anthropogenic modification exists in the low order channels in the headwaters of the Wasdale catchment (Skinner and Haycock, 2004). In contrast, evidence of straightening, embankments and walled riverbanks are present along the lower reaches of Lingmell Beck and Mosedale Beck (Skinner and Haycock, 2004). Mosedale Beck and Lingmell Beck are high energy systems and planform adjustments are expected despite the anthropogenic modifications (Skinner and Haycock, 2004).

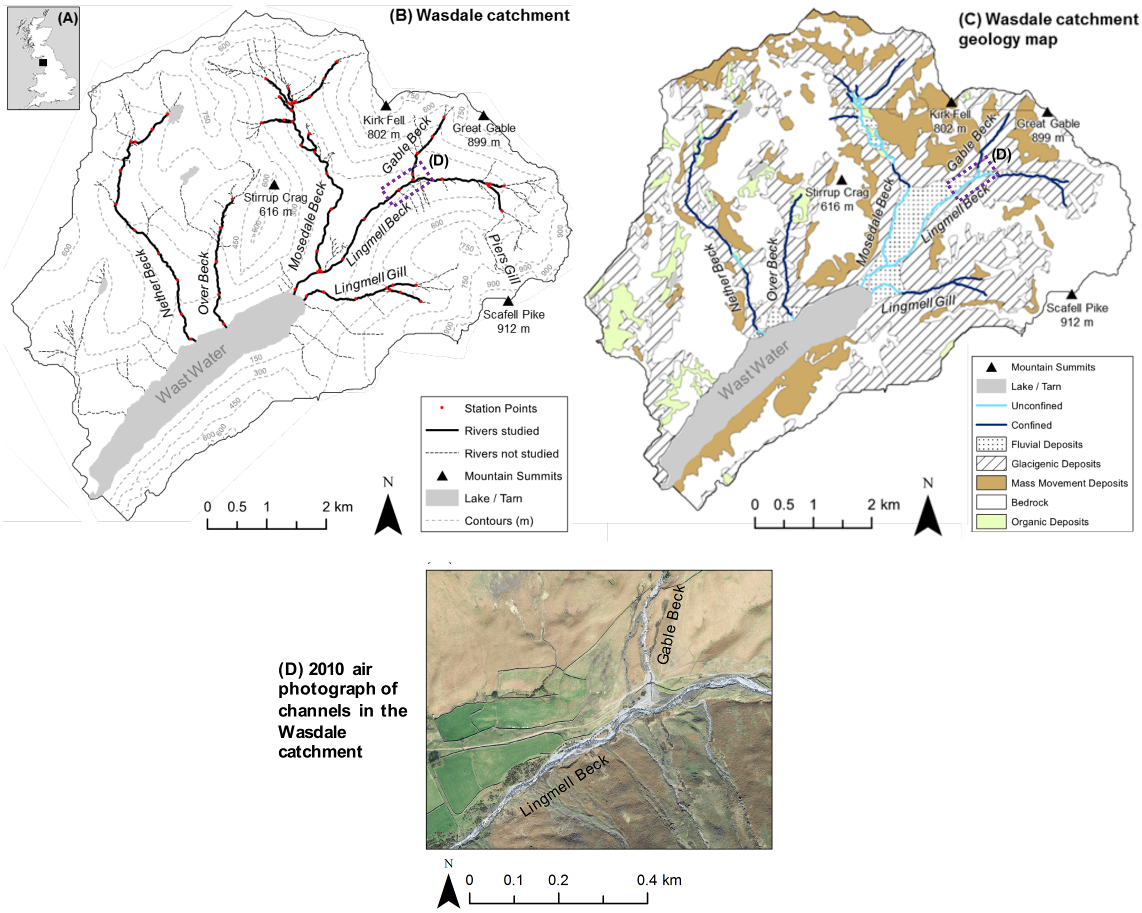


Figure 5.4. (A) Location of Lake District upland region, north-west England. (B) Wasdale catchment study area (45.4 km^2) and channel network. Rivers not studied include those that are not identifiable from historic maps and air photographs (mainly first order channels). (C) Geology map of the Wasdale catchment showing the superficial geology (source: BGS, 2016), and rivers studied that are topographically confined or unconfined. (D) Example of 2010 air photograph (Digimap, 2017) of channels in the Wasdale catchment. Area of air photograph is indicated by dashed purple box in Figs. 5.4B and 5.4C.

Historic maps and air photographs with full coverage of the Wasdale catchment are available from 1860s – 2010. Historic OS maps include the years: 1867-68 (1:10,560); 1956-57 (1:10,560); 1974-1980 (1:10,000); and air photographs: 1995 (Natural England, 0.25 m resolution), 2003-04 and 2009-10 (source: © Bluesky International Ltd, 25 cm resolution), (Table 5.1).

The use of historic maps and air photographs for identifying planform adjustment has been criticised (Hooke and Kain, 1982; Downward et al., 1994; Gurnell, 1997; Wishart, 2004). For example, historic maps were produced by different surveyors who might map the position of river banks and features differently (Harley, 1975; Hooke and Kain, 1982). Similar OS mapping approaches were adopted in the production of the historic maps and therefore river bank and features will be surveyed similarly between the different dates (Harley, 1975; Hooke and Kain, 1982). Secondly, river planform identification and active channel width measurements are sensitive to changes in discharge (flow stage) (Wishart, 2004; Gleason et al., 2014; Durand et al., 2016). Therefore, planform adjustments between two dates may reflect changes in stage height rather than geomorphic change (e.g. the presence / absence of bars) (Downward et al., 1994; Wishart, 2004; Donovan et al., 2019). However, field surveys for the production of the OS historic maps would have involved measuring morphological bankful width, and surveys would have taken longer than a single flow event (which will have a rapid stage rise and fall in upland catchments). Measurements of active channel width from air photographs are more susceptible to variations in discharge, however, air photograph capture is unlikely to have been conducted during high flow stages (bad weather conditions) (Wishart, 2004). Whilst these are known limitations with the use of historic maps and air photographs, these resources provide the best available detail of river planform over longer timescales (last 150 years) and give a unique view of historic river behaviour (Wishart, 2004).

Air photographs and historic maps were georeferenced in Esri ArcMap GIS to an OS base map in British National Grid coordinates. Error was assessed using the root-mean square error (RMSE) of the GCPs as well as in 14 independent test points (local error) (Hughes et al., 2006). A decrease in RMSE and test point error was observed between the 1860s map (RMSE = 2.6 m, test point error = 3.7 ± 2 m) and 2010 air photograph (RMSE = 0.8 m, test point error = 1.4 ± 1.4 m) (Table 5.3). Donovan et al., (2019) found that neither image/map date or resolution had a systematic influence on the degree of digitization inconsistency for a single user (Donovan et al., 2019). Median and mean planform digitization uncertainty lies between 1.5 – 2 m for historic maps and air photographs (Gurnell et al., 1994; Donovan et al., 2019). Planform adjustments mapped between the different time periods were larger than these thresholds. Whilst there are georeferencing and digitization errors associated with the historic maps and air photographs meaning that smaller adjustments will be undetected, the use of these data sources allow important spatial (regional) and temporal (past 150 years) 2D lateral patterns of planform adjustment and stability to be identified, providing a valuable insight of river behaviour. A contemporary 5 m DTM (Digimap, 2017) was used to define the baseline stream order network in GIS.

Table 5.3. Root Mean Square Error (RMSE) and local test point error following second order polynomial transformation of maps and air photographs to an OS base map.

		Test Point (Local) Error (m)	
Year of map / photo	**RMSE (m)**	**Mean**	**Std. Dev.**
1860s	2.6	3.7	2.0
1950s	3.3	4.0	1.6
1980	1.5	2.7	1.5
1995	1.4	2.0	1.0
2004	0.8	1.9	1.4
2010	0.8	1.4	1.4

5.4.2 Part 2: characterisation of fluvial system and assessment of planform evolution

Planform adjustments were mapped: (1) over the 'full period', by comparing the oldest available map (1860s) of river planform to the most recent (2010) full coverage air photograph, and (2) at higher frequency intervals using intermediate dated historic maps and air photos during the full period ('intermediate periods') (Table 5.1). Planform adjustments were mapped on second, third, fourth and fifth order channels. First order channels were not mapped as the resolution of air photographs and historic maps meant the channels <1 m wide could not easily be identified. First order channels are often topographically confined in headwater catchments, with entrenched channels or narrow valleys and therefore it is expected that there will be minimal 2D lateral planform adjustment in these channels over the period of measured change. However, it is important to recognise that first order channels can adjust vertically and supply sediment to the downstream channel network.

Station points in the Wasdale catchment (Fig. 5.4) were located at 400 m, 600 m, 800 m, and 1000 m intervals for second, third, fourth, and fifth order channels respectively. The SP interval was determined based on analysis of three SP interval resolutions (Table 5.4, Fig. 5.5). There were no statistical differences between the three SP interval resolutions at the 95 % confidence level after ANACOVA (Zar, 2010) therefore, it is assumed that geomorphic variables extracted at the lowest resolution SP interval (Table 5.4, Fig 5.5), are representative of the geomorphic variables for each stream order. Elevation values to calculate channel slope were extracted 100 m, 200 m, 300 m and 400 m upstream and downstream of the SPs for second, third, fourth and fifth order channels respectively (Table 5.5, Fig. 5.6). The spacing intervals used to extract elevation values were tested (Table 5.5, Fig. 5.6) and coincide with a similar range of previously used intervals (Alber and Piégay, 2011; Bizzi and Lerner, 2012; Lisenby and Fryirs, 2016; Martínez-Fernández et al., 2019).

Table 5.4. Different resolution station point (SP) spacing intervals (m) tested in the Wasdale catchment.

Stream order	High resolution		Medium resolution		Low resolution	
	SP interval (m)	*n*	*SP interval (m)*	*n*	*SP interval (m)*	*n*
2	100	55	200	28	400	24
3	200	54	300	39	600	25
4	300	26	400	19	800	12
5	400	3	500	3	1000	2
SP total		138		89		63

Table 5.5. Slope sensitivity analysis: distance elevation values are extracted upstream and downstream of the station points (SPs positioned at low resolution spacing interval, Table 5.4). Three distances were tested to see how it affected the calculation of slope. No statistical differences were identified between the three distance slope values (Fig. 5.6), so distance 3 is used to extract elevation values upstream and downstream of station points.

Stream order	Distance 1 (m)	Distance 2 (m)	Distance 3 (m)
2	25	50	100
3	50	100	200
4	75	150	300
5	100	200	400

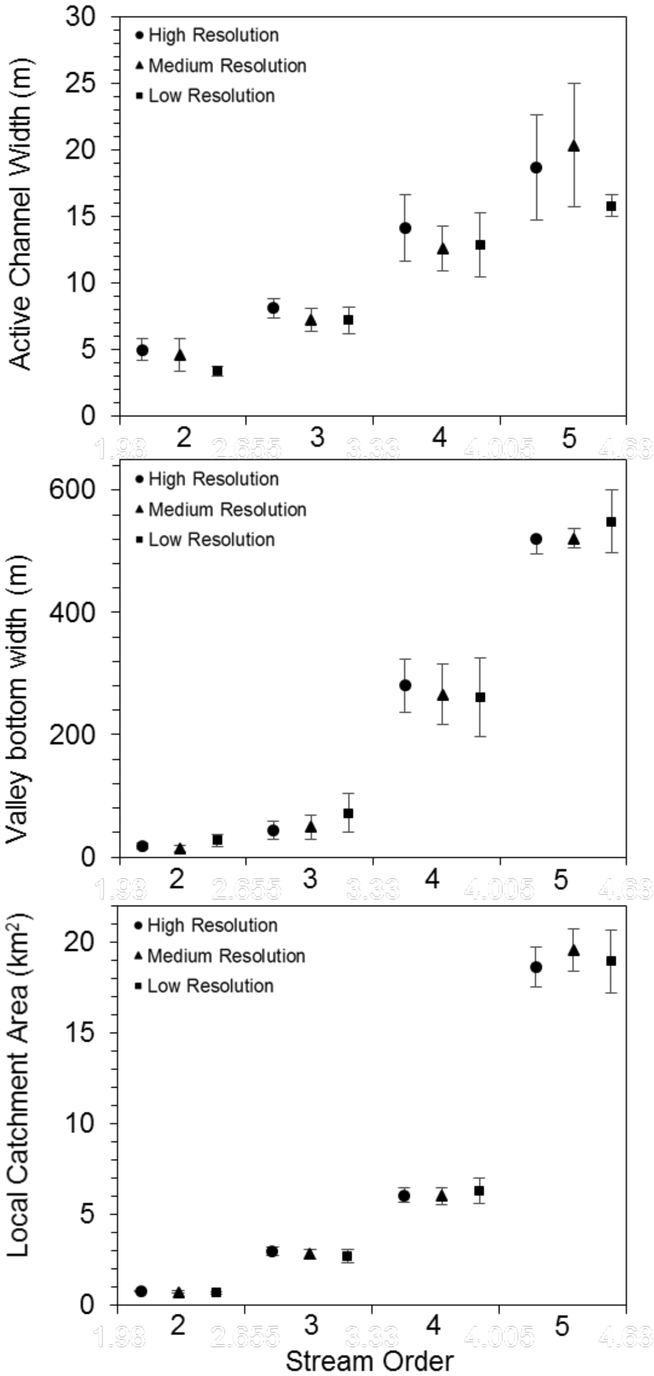


Figure 5.5. Examples of mean geomorphic characteristics extracted at high, medium and low-resolution station point spacing intervals (Table 5.4) in the Wasdale catchment. No statistically significant differences were identified between the three resolution SP intervals at the 0.05 and 0.01 confidence level.

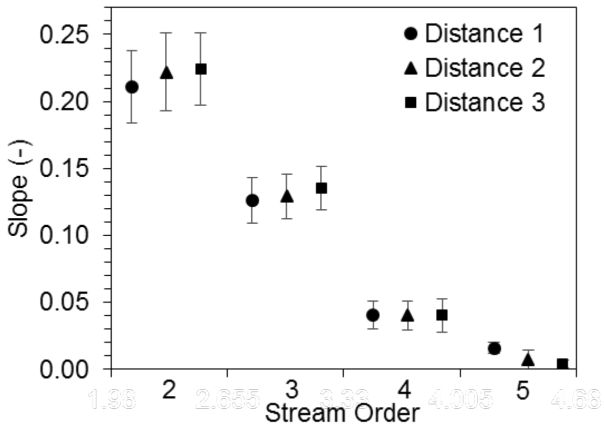


Figure 5.6. Mean slope values extracted over different distances (Table 5.5) for each stream order. There were no statistically significant differences between the three distances tested at the 0.05 and 0.01 confidence level between the distances tested, and therefore distance 3 is used.

No discharge gauging stations are located in the Wasdale headwater catchment, so to calculate stream power flow data is combined from 19 flow gauges across the Lake District upland region to produce a regional area-discharge relationship (Eq. (2)) (Fig. 5.7). The 19 flow gauges chosen have a minimum record length of 30 yr and capture a range of catchment sizes (18 - 363 km^2). Only three flow gauges occur upstream of lakes, therefore, when using the gauges downstream of lakes it is assumed that the lakes are full during bankfull flow (flood) conditions. Different flood return periods can be plotted using the available data for the region (Fig. 5.7). The coefficient of determination decreases with increasing return interval (Q_2 R^2 is 0.68, Q_{100} R^2 is 0.58), because there are fewer high magnitude events in the 30 year record (Fig. 5.7). Values of unit specific stream power are calculated for the 2 year return interval flow as this is representative of bankfull discharge in gravel-bed rivers in similar upland settings (Leopold and Wolman, 1957; Hey, 1975; Harvey, 1977; Carling, 1988; Harvey, 2001).

To understand the temporal pattern of planform adjustments and the role of flood events during the 150 year time period, gauged flow data is linked to longer term events identified using historical descriptions of major geomorphological events (i.e., landslides, changes of stream course, or large scale damage to buildings etc.) (Watkins and Whyte, 2008). Extreme flood events in the gauged data were identified by using the peak-over-threshold (POT) approach (Robson and Reed, 1999). Previous studies have defined unique POT discharge values for a catchment (i.e., Rumsby and Macklin, 1994; Pattison and Lane, 2012). However, because comparisons of peak events are made across 19 gauges, a single discharge value is not representative of the range of catchment sizes. Instead, a high POT of 75 % of the gauged flow record is set. This threshold assures only the largest flood events are used so the dataset includes an average of 1 flood event per year across the records (Robson and Reed, 1999). To reduce bias in any catchment-specific flood events identified in the gauge records, the peak events that are not observed across more than 50 % of the 19 flow gauges are removed. The cumulative number of flood events in the historical and gauged record are plotted over time to generate an overview of flood-rich and flood-poor periods across the Lake District upland region.

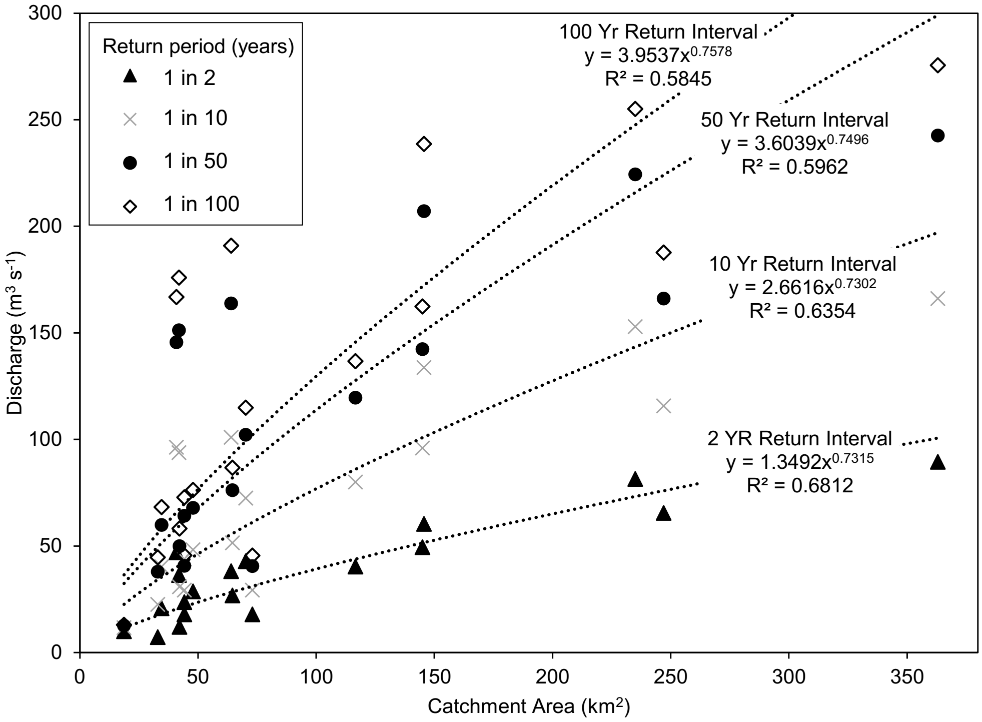


Figure 5.7. Discharge-area relationship for the 1 in 2, 1 in 10, 1 in 50 and 1 in 100 year flow event in the Lake District upland region. Generated using 19 gauging stations located throughout the upland region. Discharge data sourced from the UK Environment Agency.

5.5 Results

5.5.1 Characterisation of the fluvial system

In total, 18 channels (total length = 24 km) were studied in the Wasdale catchment, with a total of 63 SPs. There were eight second order channels, seven third order channels, two fourth order channels and one fifth order channel. The stream orders differ in length, steepness, confinement (valley bottom width) and specific stream power reflecting the longitudinal variation in the upland headwater channels (Fig. 5.8). Local mean channel slope decreases from 0.2 ± 0.09 to 0.004 ± 0.002 from second to fifth order channels (Fig. 5.8). Channel width increases by a factor of four downstream through the stream order network; second order channels have the narrowest mean channel widths (4 ± 2 m) and fourth and fifth order channels have the largest mean channels widths (16 ± 1 m). Catchment area similarly increases from second order channels (mean catchment area = 0.8 ± 0.4 km^2) to fifth order channels (19 ± 1.5 km^2) (Fig. 5.8). Mean valley bottom width increases by a factor of 18 downstream from 31 ± 43 m in second order channels to 550 ± 30 m in fifth order channels (Fig. 5.8). Mean bankfull stream power decreases by a factor of 25 downstream from 620 ± 305 W m^{-2} in second order channels to 25 ± 8 W m^{-2} in fifth order channels (Fig. 5.8).

Planform adjustments in the Wasdale catchment are assessed (1) over the 'full period' by comparing the earliest historic map and recent air photograph, 1860s - 2010 (150 year); and (2) at 'intermediate periods' at higher frequency intervals (1860s – 1950s; 1950s – 1980; 1980 – 1995; 1995 – 2004; 2004 – 2010) during the 150 year period.

5.5.2 Planform adjustments

5.5.2.1 Full period (1860s – 2010) results

Over the full period, 114 planform adjustments were identified (Fig. 5.9A). The total length of channels mapped as stable was 68 % (16 km) and adjusting was 32 % (8 km). Bar adjustments were the most common forms of adjustment (n = 68, 60 %, Fig. 5.9A) and affected an average of 9 % of the channel length (Fig. 5.10B). The mean percentage of channel length affected by bend adjustments (n = 19, 17 %) was 6 %; boundary adjustments (n = 12, 11 %) was 17 % and width adjustments (n = 15, 13 %) was 11 % (Fig. 5.10). The highest frequency of planform adjustments occurred in third order (n = 45, 40 %) and fourth order (n = 48, 42 %) channels (Fig. 5.9A) where catchment area increases and channels become topographically unconfined (Fig. 5.8). The 2D stable reaches (n = 66) affected an average of 20 % of the channel length over the full period (Fig. 5.11).

Over the full period of analysis, 43 of the mapped planform adjustments (38 % of the total number of adjustments) occurred in combination with another planform adjustment type. Thirty percent of the total combined planform adjustments were bar and width adjustments, 28 % were bar and bend adjustments, 28 % were bar and boundary adjustments, 5 % were boundary and width adjustments, and 9 % were bar, boundary and width adjustment combinations.

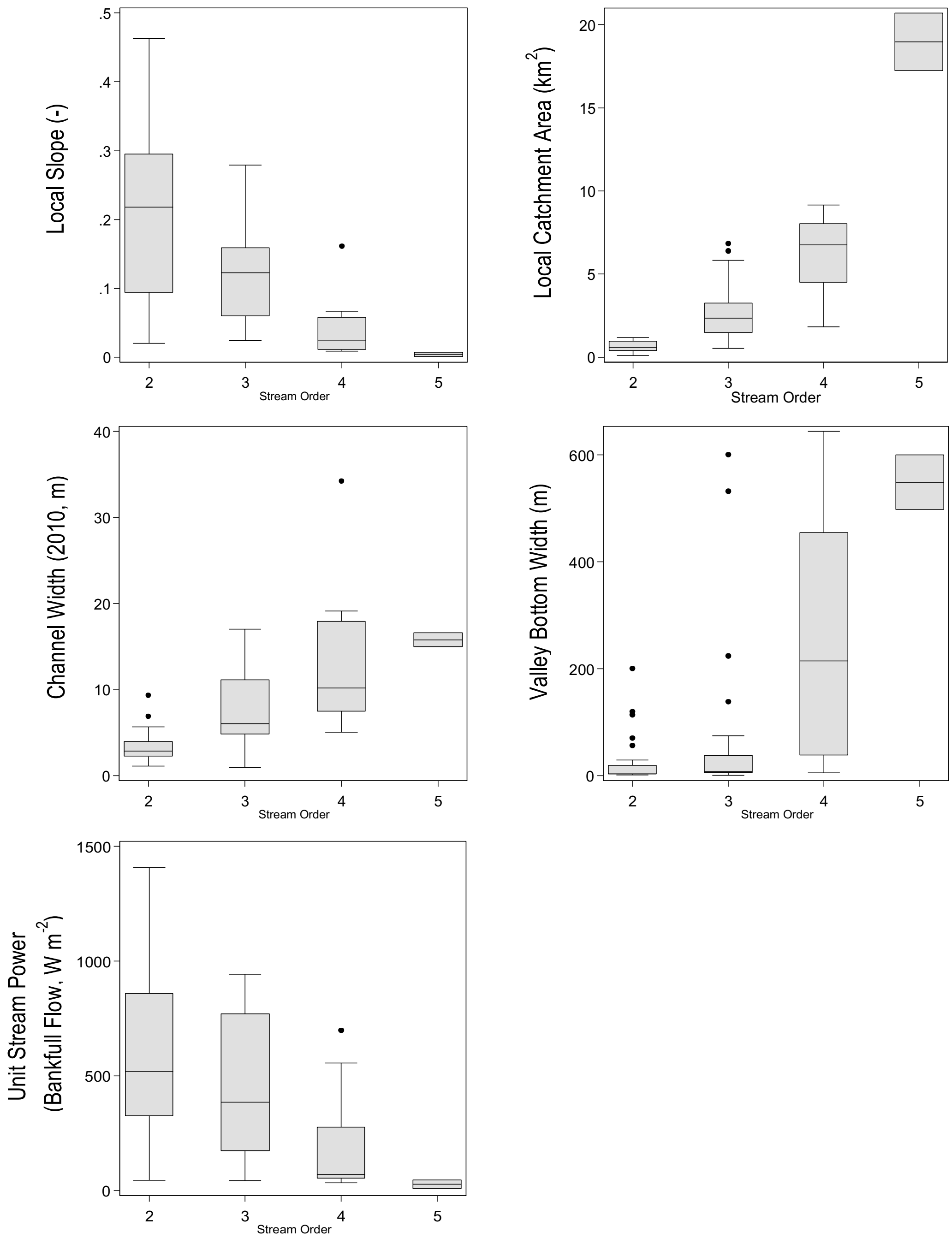


Figure 5.8. Box plots showing the slope, catchment area, valley bottom width and unit specific stream power characteristics extracted from the station points for each stream order in the Wasdale catchment. Statistically significant differences were identified between the mean of the geomorphic variables between each stream order at the 95 % confidence level.

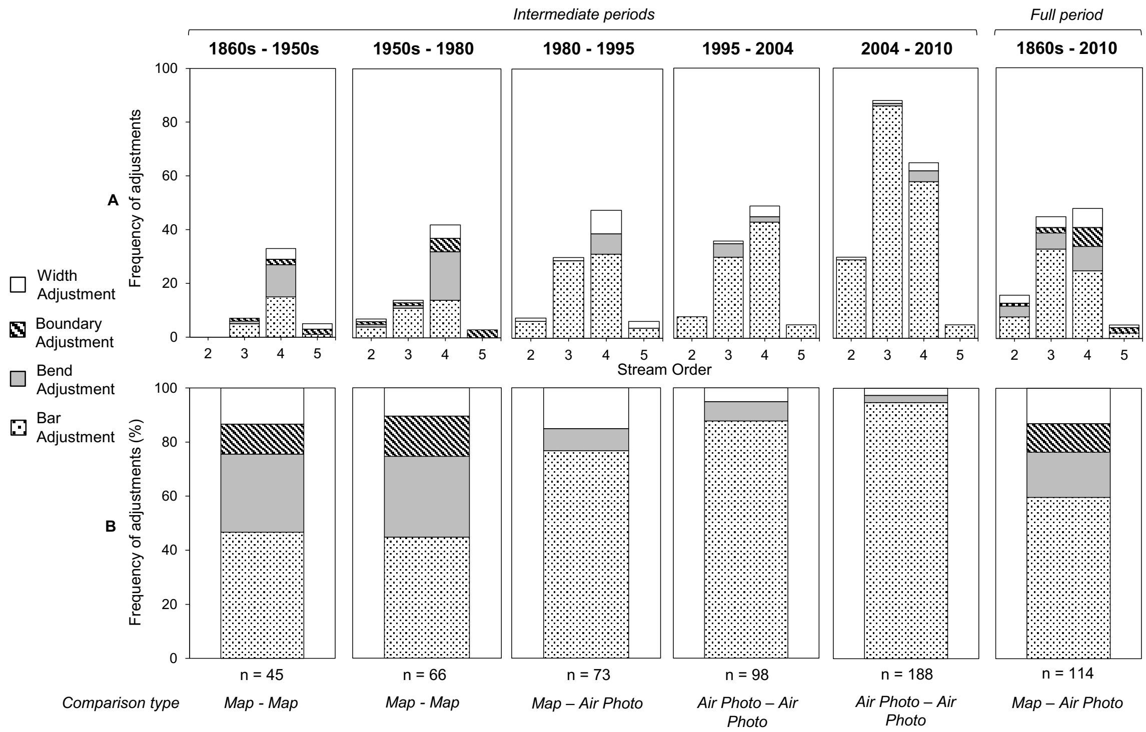


Figure 5.9. (A) Frequency and (B) percentage frequency of planform adjustments by stream order, in the Wasdale catchment, UK, for the available historical maps and air photographs.

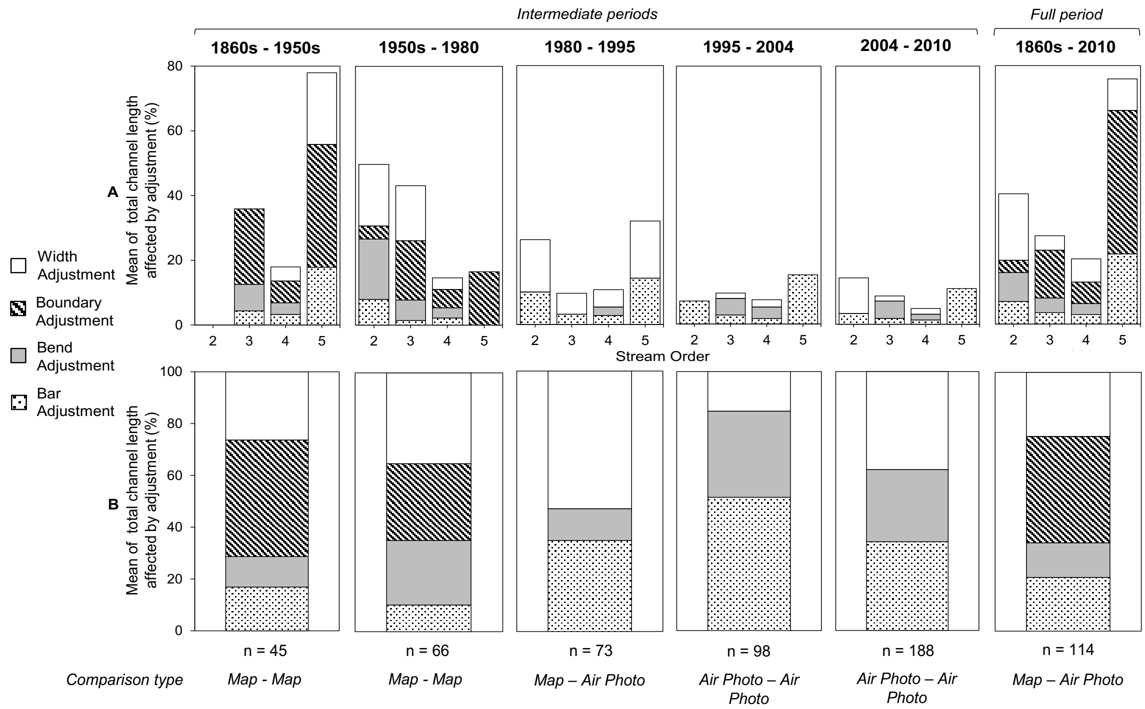


Figure 5.10. Mean percentage of channel length affected by planform adjustment by stream order (A) and mean percentage of channel length affected by planform adjustment (B) in the Wasdale Catchment, UK, for the available historical maps and air photographs (1860s – 2010).

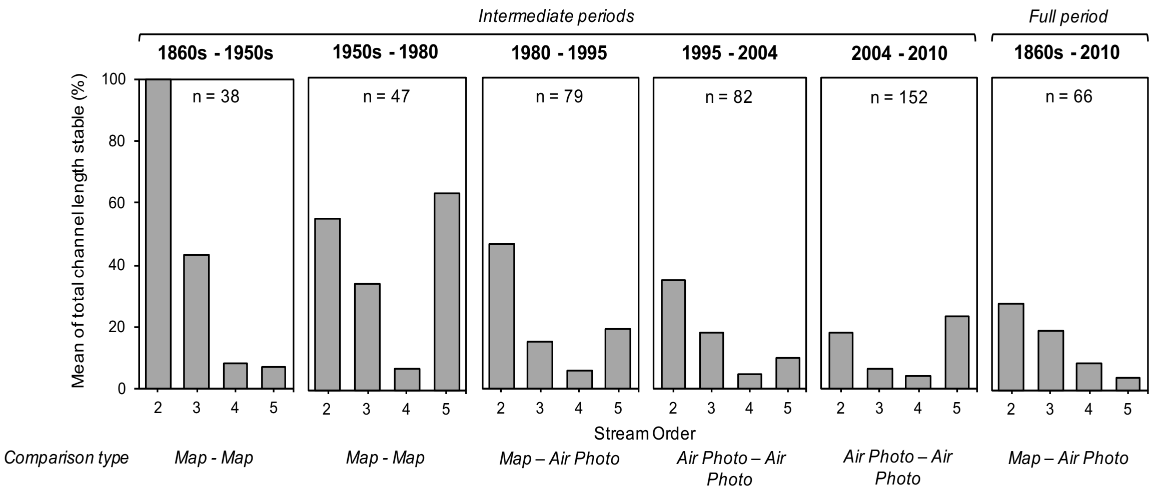


Figure 5.11. Mean percentage length of stable reaches for each time period plotted against stream order for the Wasdale catchment, UK.

5.5.2.2 Intermediate period results

In the shorter time interval comparisons, bar adjustments were the most frequent planform adjustment observed (1980 – 1995, n = 56; 1995 – 2004, n = 86; 2004 – 2010, n = 178), (Fig. 5.9). Boundary adjustments were observed in the 1860s – 1950s, and 1950s – 1980 intermediate time periods, however, these adjustments were absent after the 1980 period (Fig. 5.9).

A reduction in the mean percentage of channel length affected by planform adjustments is observed over the stream order network in the intermediate time periods (Fig. 5.10). Planform adjustments in 1860-1950s and 1950s-1980 affected an average of 40 % of the channel length, whereas adjustments over the shorter time span intervals from 1980-1995, 1995-2004 and 2004-2010 affected an average of 22 – 13 % of the channel length (Fig. 5.10). This coincides with a reduction of the occurrence of boundary adjustments from 1980 – 2010, which affected a mean of 17 % of the river channel length from 1860s – 1980 (Figs. 5.9 and 5.10).

Second order channels have the highest mean percentage of length categorised as 2D stable over 1860s – 1950s (100 %), 1980-1995 (47 %) and 1995-2004 (35 %) (Fig. 5.11). Over the period of analysis there has been a progressive reduction in the overall length of channel mapped as stable (Fig. 5.11), this is likely caused by an increase in the frequency of bar adjustments being mapped from 1980s onwards as a result of the changing resolution and type of data source used.

Combined planform adjustments were identified in all of the intermediate time periods. From 1860s – 1950s, 33 % (n = 15); 1950s – 1980, 24 % (n = 16); 1980-1995, 25 % (n = 18); 1995 – 2004, 18 % (n =18) 2004 – 2010, 8 % (n = 15) of river planform adjustments were combined processes. The most frequently combined planform adjustments during the intermediate periods were bend and bar adjustments (n = 35).

5.5.3 Geomorphic variables of planform adjustment and stable reaches

To identify the key geomorphic characteristics influencing the location and extent of planform adjustments, a comparison was made between the geomorphic variables extracted from the SPs and the planform adjustment and stable reach data for all time periods (full period and intermediate periods) (Fig. 5.12). In total, 1048 2D adjustment and stable reaches were compared, of this frequency: bar adjustments accounted for 42% (n = 438); bend adjustments 7% (n = 70); boundary adjustments 3% (n = 27); width adjustments 5% (n = 49); and the frequency of stable reaches was 44% (n = 464).

Stable reaches were found to have differences between planform adjustment mean geomorphic variables over the full data set (Table 5.6). Stable reaches (n = 464) had a mean channel width of 8 ± 5 m, slope of 0.1 ± 0.08, local catchment area of 3.4 ± 3.3 km^2, valley bottom width of 110 ± 157 m and bankfull unit stream power of 424 ± 260 W m^{-2} (Fig. 5.12). The 2D stable reaches were most commonly found in confined second order channels, where bend and boundary adjustments are less likely because of limited space for lateral adjustment (Fig. 5.12). Adjustment reaches (n = 584) had a mean channel width of 11 ± 5.6 m, slope of 0.08 ± 0.07, local catchment area of 4.7 ± 4.1 km^2, valley bottom width of 170 ± 194 m and bankfull unit stream power of 325 ± 250 W m^{-2} (Fig. 5.12). Boundary adjustments occurred in unconfined valley reaches, where mean valley bottom width is 430 ± 165 m, mean slopes are 0.04 ± 0.06, and where there is a large mean upstream catchment area of 9.4 ± 6 km^2 (Fig. 5.12). In contrast, bar adjustments were less restricted to unconfined valleys and low slopes, occurring on mean valley bottom widths of 145 ± 180 m and where mean slopes were 0.09 ± 0.08.

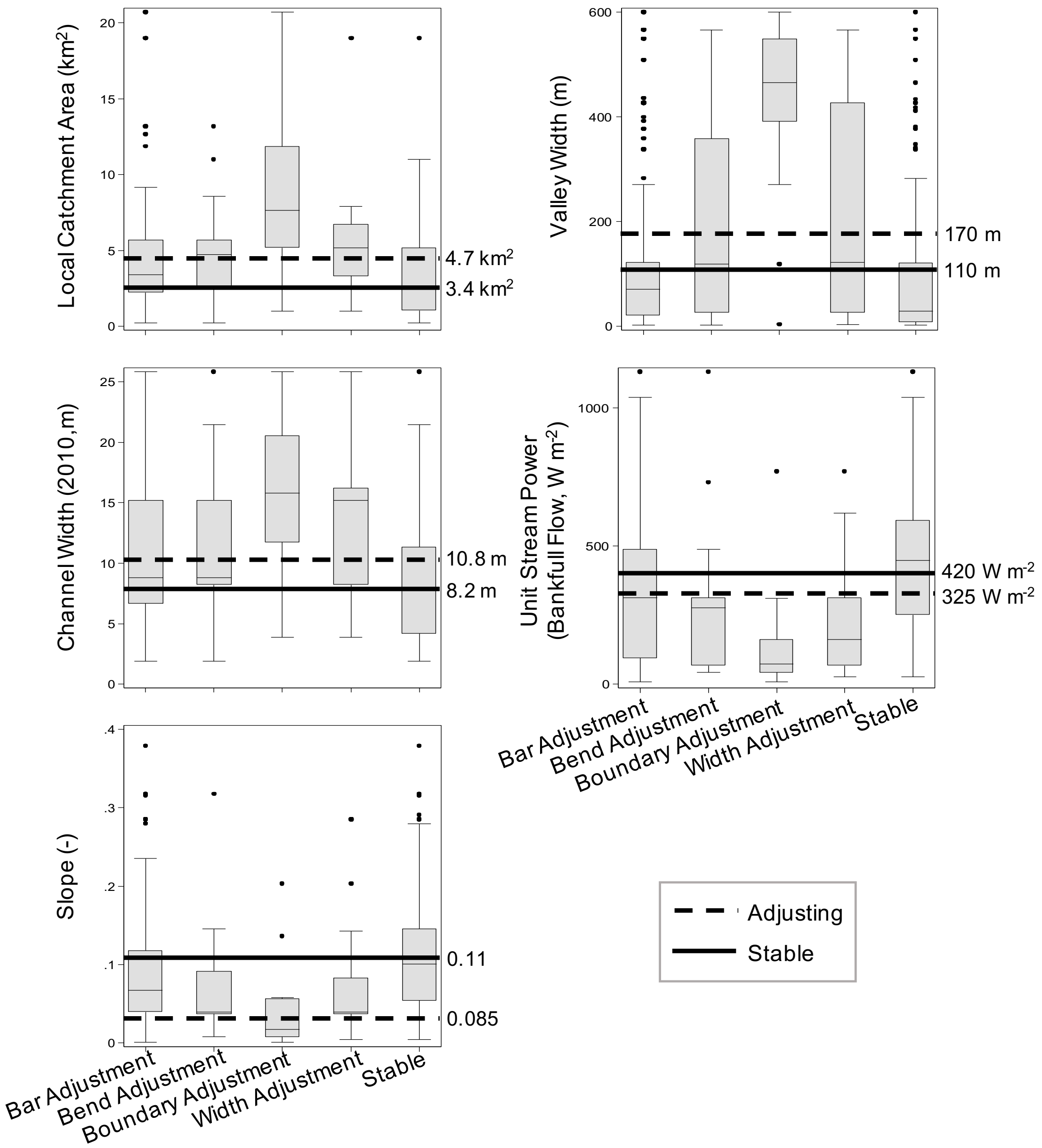


Figure 5.12. Box plots showing the geomorphic variables for each planform adjustment category for the full-time period analysis (1860s – 2010). Continuous lines represent the mean geomorphic value for stable reaches, dashed lines indicate the mean geomorphic values for adjusting reaches.

A one-way ANOVA and Tukey (HSD) was performed to identify if a statistically significant difference between the mean geomorphic variables and the adjustment and stable reaches for each stream order was present (Table 5.6). The length of the fifth order channel was truncated by Wast Water and was excluded from the statistical analysis because of its short 590 m length and the small number of observed adjustments (n = 38, 4 % of total of adjustments studied), therefore, results focus on the ANOVA analysis of planform data for second, third and fourth order channels.

Third and fourth order channels display the highest number of significant differences (n*) (n* = 22) between adjustment types and the geomorphic variables (Table 5.6) compared to second order channels (n* = 5). Second order channels have steeper channel slopes and higher unit specific stream power values (Fig. 5.8), however, they are characterised by a narrower range of values for catchment area (0.2 - 1.7 km2), channel width (2 – 12 m) and valley bottom width (2 – 210 m) compared to third and fourth order channels (Fig. 5.8). In confined, second order channels the space available for channel adjustment is restricted and therefore there are fewer significant differences between the geomorphic variables and adjustment types (n* = 5) (Table 5.6).

In contrast, the geomorphic variables (catchment area, valley bottom width, channel width) increase in third and fourth order channels (Fig. 5.8) and display the highest number of statistically significant differences (n* = 22) between adjustment types and the geomorphic variables (Table 5.6). The highest number of statistical differences identified in third and fourth order channel planform adjustments are associated with valley bottom width (n* = 9) (Table 5.6).

The highest number of significant differences between geomorphic variables and planform adjustments were between bar and boundary adjustments (n* = 7), and boundary and width adjustments (n* = 5) in third and fourth order channels (Table 5.6). Bar adjustments in third and fourth order channels occurred where mean valley bottom width was 145 ± 170 m, boundary adjustments occurred where the mean valley bottom width was 430 ± 140 m and width adjustments occurred where the mean valley bottom width was 240 ± 220 m. Boundary adjustment frequency was lower in second order channels because topographic confinement limits lateral adjustment (Fig. 5.4C). The lowest number of significant differences in second, third and fourth order channels identified were between bend and bar adjustments (n* = 1) and bar and width adjustments (n* = 1); these adjustments often occurred in combination. The combined data column (Table 5.6) suggest significant differences were observed between most geomorphic variables, but the highest number of statistical differences could be identified by differences in channel width and valley bottom width (n* = 8); these statistical differences are concentrated in third and fourth order channels.

Table 5.6 shows the one-way ANOVA analysis results comparing adjustment types and the geomorphic variables between each stream order. The results indicate that adjustments and geomorphic characteristics have statistical differences and are scaled between each stream order. Second and fourth stream order channels have the highest number of significant differences in all geomorphic variables ($n^* = 24$). For example, stable reaches in second order channels are characterised by valley bottom widths of 30 ± 40 m, channel slopes of 0.2 ± 0.09, catchment areas of 0.8 ± 0.4 km^2 and the highest bankfull stream powers of 600 ± 300 W m^{-2}. In contrast, stable reaches in fourth order channels are characterised by valley bottom widths of 230 ± 180 m, channel slopes of 0.04 ± 0.02, catchment area of 6 ± 2 km^2 and stream power values of 200 ± 145 W m^{-2}. There are significant differences, but between fewer geomorphic variables between neighbouring stream orders (Table 5.6). For example, between second and third order channels $n^* = 15$, and fourth and fifth order channels $n^* = 9$. Catchment area ($n^* = 25$) and slope ($n^* = 23$) have the highest number of statistical differences between each stream order (Table 5.6). This is because of the changing hydraulic geometry laws downstream the stream order network (Richards, 1982; Gordon, 1996).

Table 5.6. One-way ANOVA and Tukey (HSD) results showing statistically significant differences (at 95% confidence interval p value <0.05), between planform adjustments, stable reaches, geomorphic variables and stream order. Dots indicate the presence of a statistically different relationship. *S* is local slope (-), *A* is local catchment area (km^2), W is channel width (2010, m), *VW* is valley bottom width (m), ω is the 2 yr Return Interval Specific Stream Power ($W\ m^{-2}$). Combined column represents analysis for all stream orders, green highlighted columns shows the geomorphic variables with the highest number of statistically significant differences.

	Stream Order 2					Stream Order 3					Stream Order 4					Combined				
Comparison between adjustment categories	*S*	*A*	*W*	*VW*	*ω*	*S*	*A*	*W*	*VW*	*ω*	*S*	*A*	*W*	*VW*	*ω*	*S*	*A*	*W*	*VW*	*ω*
p value	0.008	0.111	0.003	0.441	0.056	0.114	0.342	0.000	0.000	0.010	0.015	0.000	0.008	0.000	0.076	0.000	0.000	0.000	0.000	0.000
Bar Adjustment vs Bend Adjustment	•															•		•		•
Bar Adjustment vs Boundary Adjustment								•	•		•	•	•	•	•	•	•	•	•	•
Bar Adjustment vs Width Adjustment	•															•	•	•	•	•
Bar Adjustment vs Stable			•					•	•								•	•	•	•
Bend Adjustment vs Width Adjustment								•	•			•		•			•	•	•	
Bend Adjustment vs Boundary Adjustment																•		•	•	•
Bend Adjustment vs Stable			•																	
Boundary Adjustment vs Width Adjustment								•	•			•	•	•		•	•	•	•	•
Boundary Adjustment vs Stable												•		•			•		•	
Width Adjustment vs Stable			•					•	•							•	•	•	•	•

Table 5.7. One-way ANOVA and Tukey (HSD) results showing statistically significant differences (at 95% confidence interval, p value <0.05), between stream orders and planform adjustments, stable reaches, and geomorphic variables. Dots indicate the presence of a statistically different relationship. *S* is local slope (-), *A* is local catchment area (km^2), W is channel width (2010, m), *VW* is valley bottom width (m), ω is the 2 Year Return Interval Stream Power Stream ($W\ m^{-2}$).

	Bar Adjustment					Bend Adjustment					Boundary Adjustment					Width Adjustment					Stable				
Comparison between Stream Orders	*S*	*A*	*W*	*VW*	*ω*	*S*	*A*	*W*	*VW*	*ω*	*S*	*A*	*W*	*VW*	*ω*	*S*	*A*	*W*	*VW*	*ω*	*S*	*A*	*W*	*VW*	*ω*
p value	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	0.000	0.000	0.000	0.086	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2 vs 3	•	•	•	•	•						•			•	•	•	•				•	•	•		•
2 vs 4	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
2 vs 5	•	•	•	•	•						•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
3 vs 4	•	•	•	•	•	•	•	•		•	•	•				•	•				•	•	•	•	•
3 vs 5	•	•	•	•	•						•	•			•	•	•		•	•	•	•	•	•	•
4 vs 5	•	•		•	•							•					•		•			•		•	

5.5.4 Flood-rich and flood-poor periods and the timing of planform adjustments

To understand the temporal pattern of channel planform adjustments, archival and flow gauge information is used to identify flood-rich and flood-poor periods (Fig. 5.13A). Five flood-rich periods were identified across the Lake District upland region that correspond to previously reported flood-rich periods in northern UK and north-western Europe (Macklin and Lewin, 1998; Pattison and Lane, 2012; Macdonald and Sangster, 2017) (Fig. 10A). Figure 5.13A shows the regional pattern of flood-rich and flood-poor periods from multiple flow gauges in the Lake District (19 gauges), however, individual catchments can be affected by local flood conditions. For example, Johnson and Warburton (2002) reconstructed local historic flood events using lichenometry in Raise Beck (NGR NY 330 118, central Lake District, ~15 km north-east of the Wasdale catchment) (Fig. 5.13A). Three of the Raise Beck flood events coincide with the regional flood-rich periods and three do not, highlighting local variability in flood conditions (Fig. 5.13A). Because there are no flow records in the Wasdale catchment only the regional flood data is used, but it is acknowledged there will likely be local differences in flood histories between valleys.

Figure 5.13B shows the average length of planform adjustments types for each time period. Boundary adjustments were not observed after the 1980s (Fig. 5.13B). The average length of channel affected by bend and bar adjustments has been relatively consistent over all time periods (Fig. 5.13B). Width adjustments affected a greater length of channel planform in 1860s-1950s, 1950s-1980 and 1980-1995 time periods (Fig. 5.13B). The mean percentage length of stable reaches over time decreased (Fig. 5.13). The changing resolution of the map and air photographs, and the length of sampling interval over which planform adjustments are mapped, will influence the type and frequency of adjustments identified. For example, air photograph resolution (0.25 m) will enable smaller adjustments to be identified (i.e., bar adjustments), reducing the length of channel categorised as 2D stable (Fig. 5.9). Similarly, the length of historic map and air photograph sampling interval decreases towards the present, which will impact the number of recorded channel adjustments depending on whether a flood-rich period falls between two observational epochs or not. Despite these limitations, this is the best available catchment scale data of 2D planform adjustments, stable reaches and historic flood events over the 150 year time period.

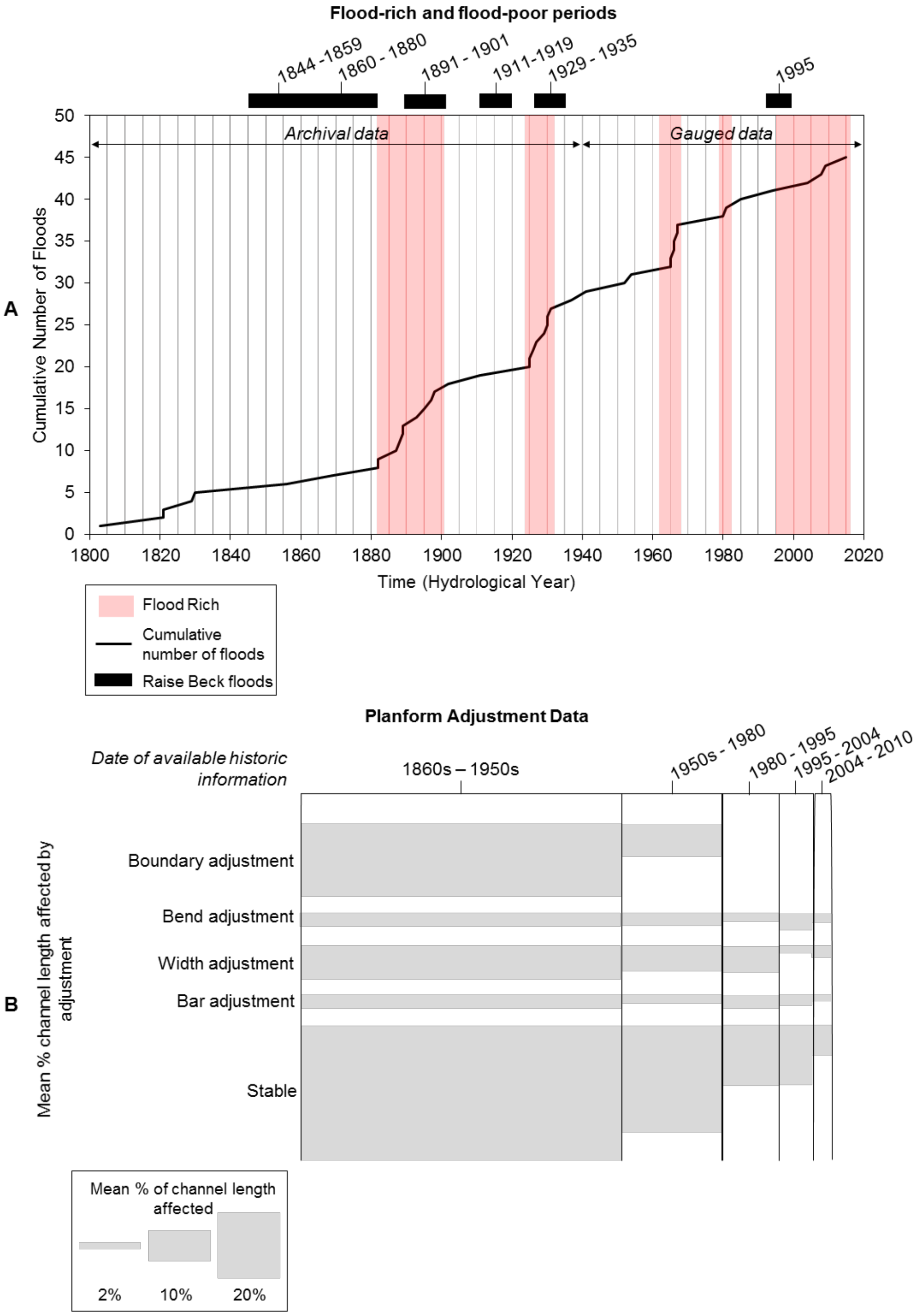


Figure 5.13. (A) Cumulative number of high flow events as a function of time for the Lake District upland region. Peak flow data is based on documented extreme flood events from archival evidence and gauged data (19 gauges) that represent POT flows. Where the gradient of the line is steep it indicates a high frequency of large flood events and flood-rich periods (red bars). A local flood record at Raise Beck (NGR NY 330 118) from Johnson and Warburton (2002) is plotted against the regional flood record. (B) Mean length of channel affected by planform adjustment (%) (height of grey bars is proportional) for each time period map / air photograph comparison. Grey bar length represents the time span between available map/photo comparisons.

5.6 Discussion

5.6.1 Catchment scale patterns and controls of 2D planform adjustment

In this Chapter, a systematic methodology to quantify historic 2D channel planform adjustments, stable reaches and the associated geomorphic variables at the catchment scale has been developed and applied. Previous river planform adjustment studies have emphasised the dynamic nature of upland river channels (Newson, 1989). In the Wasdale catchment, a similar picture emerges with 32 % of the total channel network length classified as adjusting between 1860s-2010 (Fig. 5.14). Similar patterns of actively adjusting reaches have been identified in British rivers using historical sources (Ferguson, 1981). For example, Lewin et al. (1977) identified that 25% of 100 randomly surveyed channel reaches in Wales were adjusting over a period of 44 – 78 years. Hooke and Redmond (1989a) estimated that over an 89 year period (1870-1959), 35% of UK upland rivers experienced planform adjustment.

The structure of a catchment, primarily determined by the geological and glacial history, plays an important role in influencing sediment continuity and patterns of planform adjustment (Milne, 1983; Downs and Gregory, 1993; Thomas, 2001; Sear and Newson, 2003; Fryirs et al., 2009). In headwater catchments, low order channels are often topographically confined (Milne, 1983; Montgomery and Buffington, 1993; Downs and Gregory, 1993) and have been termed ‘resistant’ or ‘insensitive’ to planform adjustments (Brunsden and Thornes, 1979; Sear et al., 2003; Fryirs et al., 2009; Thoms et al., 2018; Piegay et al., 2018; Fuller et al., 2019). In the Wasdale case study, second order channels were topographically confined (mean valley bottom widths of 31 ± 43 m, Fig. 5.8) and local bar adjustments were the most frequent form of adjustment (Fig. 5.9). The presence of bar adjustments can indicate the channels are locally active in terms of sediment supply and transfer, and therefore show little change to the channel boundaries over time (Fig. 5.9). One exception to this general result was observed in Gable Beck, a second order channel, where a local cut off and width adjustment (1950s – 1980) occurred where valley bottom width expands, allowing the channel to become locally unconfined (Figs. 5.4C and 5.14). Overall, however, topographically confined low order channels displayed patterns of persistent 2D stability, indicating a high level of sediment continuity and relative balance between sediment input and output.

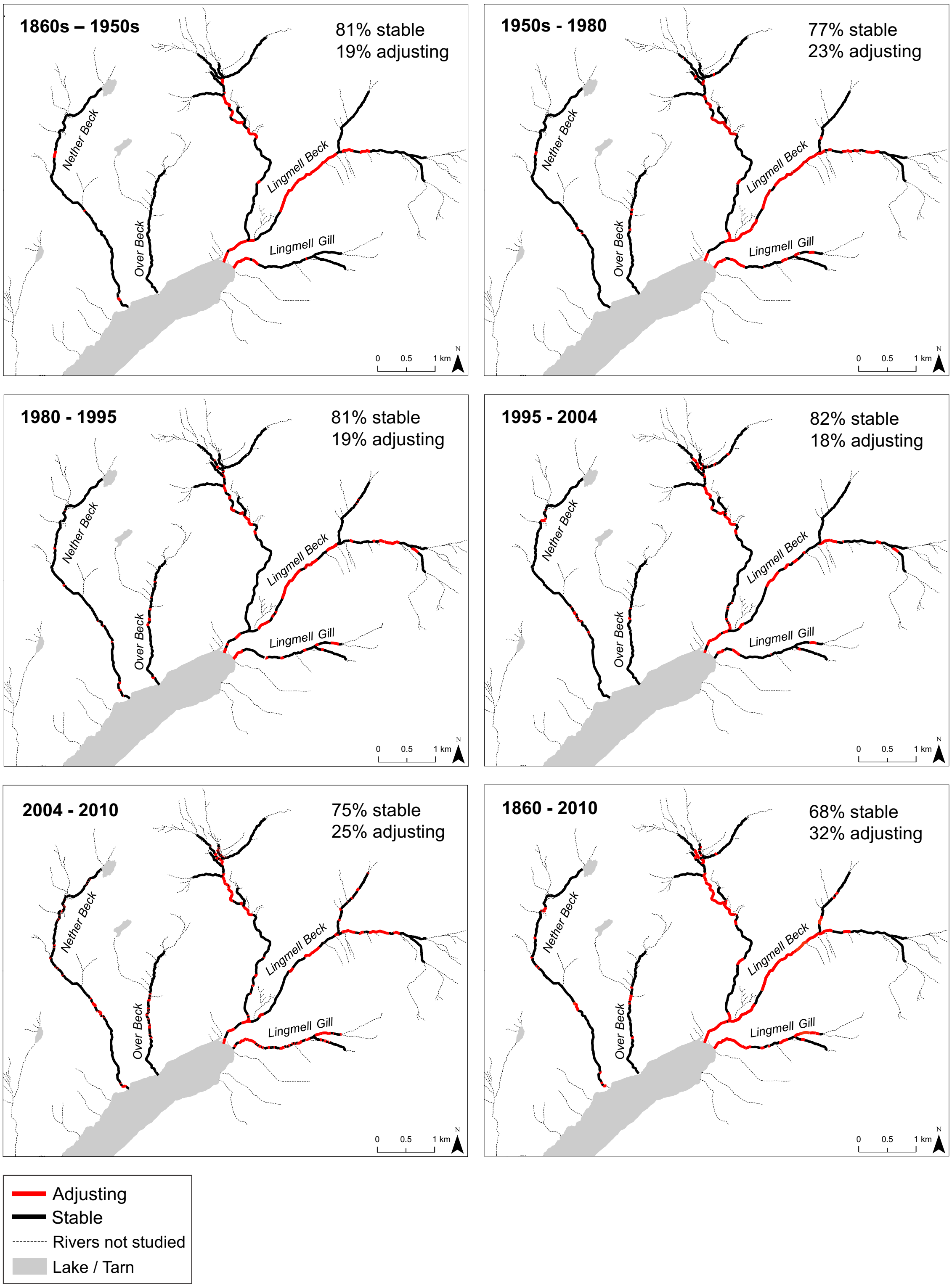


Figure 5.14. Spatial pattern and percentage length of stable and adjusting reaches for all time periods of analysis in the Wasdale catchment, UK.

In contrast, downstream in high order channels in the floodplain valley transfer zone, valley bottom width increases markedly (Fig. 5.8) creating space (Schumm, 1977; Church, 1996) for the channel to interact with floodplains laterally (Ibisate et al., 2011). The highest frequency of planform adjustments was observed in third to fifth order channels (Fig. 5.9). The most active adjustment locations were observed in the downstream reaches of Lingmell Beck (fourth and fifth order channels) where mean valley bottom width was 410 ± 110 m, allowing room for lateral planform adjustments. Lingmell Beck also had a low mean channel slope 0.03 ± 0.01, large mean catchment area 12 ± 1.7 km^2, and low mean stream power 130 ± 80 W m^{-2} (Fig. 5.8). Unconfined reaches with low specific stream powers can accommodate sediment deposition (Knighton, 1999; Reinfelds et al., 2004; Lea and Legleiter, 2016), which can lead to local aggradation (poor sediment continuity) and super-elevation of the bed in relation to the floodplains, which can instigate larger scale adjustments such as avulsions (Jones and Schumm, 1999). This is evidenced by large depositional areas in the mid to lower reaches of Lingmell Beck (Skinner and Haycock, 2004).

McEwen (1994) identifies similar changes in river channel planform stability along the River Coe, Scotland. In the upstream reaches, the River Coe is relatively confined and stable, however, downstream the channel floodplain valley, slope and stream power changes, and the channel planform transitions to a wandering gravel-bed river where the channel actively reworks the floodplains and sediment aggrades in the channel (McEwen, 1994). The floodplain valley transfer zone represents an important sediment source and store regulating sediment continuity downstream over different timescales (Werritty and Ferguson, 1980; Ferguson, 1981). Joyce et al. (2018) highlight the importance of valley floodplains in storing sediment during extreme flood events causing sediment attenuation at the channel outlet. In the Wasdale catchment, persistent adjustment reaches over the last 150 year indicate locations of continual sediment erosion and deposition in the floodplain valley transfer zone. For example, where the channel becomes unconfined in the mid to lower reaches of Lingmell Beck, repeated bar, bend and width adjustments were recorded in the intermediate periods of analysis (Fig. 5.14) and are evidenced by depositional features (Skinner and Haycock, 2004). Sediment continuity therefore varies at the event scale and over much longer timescales *c.* 150 years.

The statistical analysis investigated the importance of the different types of river planform adjustment in relation to catchment geomorphic variables (Table 5.6, Fig. 5.12). Valley bottom width and channel width could be used to identify differences in stable reaches, bend, boundary, width and bar adjustments across the catchment (Table 5.6). However, the analysis highlighted that not one geomorphic variable alone could be used to define a particular type of river planform adjustment. This is because planform adjustments occur in response to interactions of multiple geomorphic variables. Second, it is difficult to identify the geomorphic variables of individual planform adjustment categories because planform adjustments can occur in combination. Figure 5.15 summarises the frequency of interactions between planform adjustment categories in the Wasdale catchment. In the full-time period analysis (1860s – 2010), 38 % (n = 43) of river channel planform adjustments identified were coincident with another planform adjustment. Bar adjustments are the most frequent type of adjustment and are associated equally with channel boundary, width and bend adjustments (Fig. 5.15). This result is to be expected given that the bar can be regarded as the fundamental geomorphic unit in fluvial systems (Church and Rice, 2009; Rice et al., 2009) and its morphodynamics indicate the state of sediment flux (continuity) within a particular river reach. This underpins the basis of the methodology applied here.

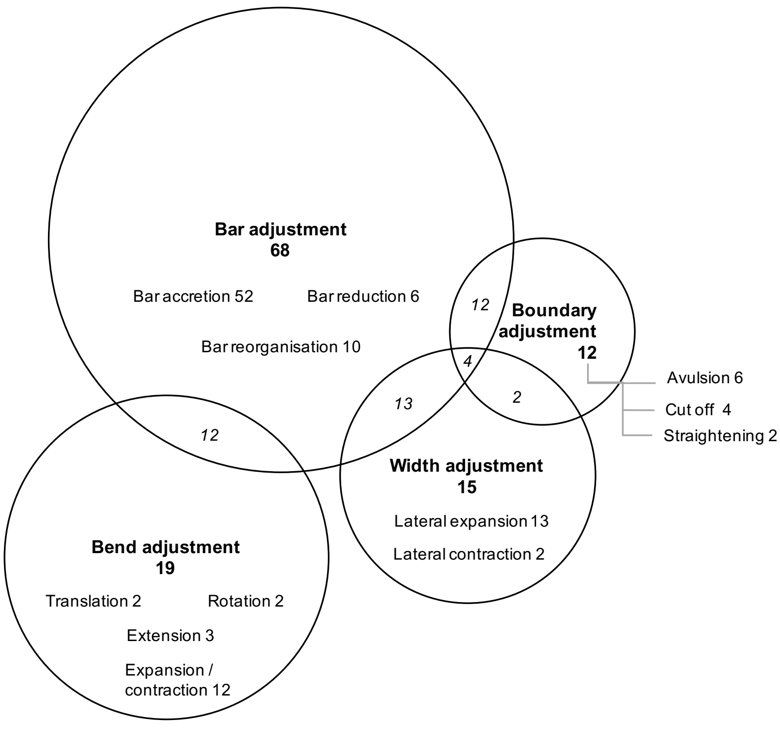


Figure 5.15. Venn diagram showing the frequency of interactions between planform adjustment categories in the Wasdale catchment for the full period of analysis 1860s - 2010. Circles are proportional to the number of observed primary adjustments. Numbers in bold show the total frequency of adjustments for each group, numbers in italics represent the total number of combined adjustments between the groups.

5.6.2 Historic pattern of river channel planform adjustment

The temporal pattern of river planform adjustments in many upland catchments has been linked to the incidence and severity of major floods (Wolman and Miller, 1960; Anderson and Calver, 1980; Milne, 1982; McEwen, 1989; Rumsby and Macklin, 1994; McEwen, 1994; Werritty and Hoey, 2004). High magnitude flood events can cause the erosion of river banks, initiate high sediment transport rates, leading to subsequent sediment deposition in the channel and on floodplains as peak flows recede (e.g., Fuller, 2008; Milan, 2012; Joyce et al., 2018; Heritage and Entwistle, 2019). Sediment deposition can block the channel promoting channel avulsion or chute and neck cut offs across the floodplain (Anderson and Calver, 1980; McEwen, 1994; Jones and Schumm, 1999). In the Wasdale catchment, boundary adjustments (avulsions, cut offs) occurred between 1860s – 1950s and 1950s-1980, coinciding with four flood-rich periods in the Lake District region (Fig. 5.13). No boundary adjustments were identified from 1980 – 2010, despite this being a flood-rich period documented across the Lake District upland region (Pattison and Lane, 2012).

The relationship between the type and extent of planform adjustments is complicated by the fact that channel response to floods can vary from catchment to catchment (Warburton et al., 2002). First, the lack of flow gauge records in the Wasdale catchment limits the identification of catchment specific flood events that drive planform adjustments. Therefore, the lack of boundary adjustments observed after the 1980 period could be because there has not been a local flood of sufficient magnitude for geomorphic adjustment. The Raise Beck flood study (Johnson and Warburton, 2002) highlights that there is variability in river response to localised flood events compared to the Lake District regional flood record (Fig. 5.13A). Recent work reconstructing detailed flood chronologies from lake sediment records (Chiverrell et al., 2019) and floodplain sediment cores (Jones et al., 2012; Fuller et al., 2019) provides an alternative means of developing catchment flood histories that are catchment specific and extend beyond the era of documented flood events. Second, the lack of observed boundary adjustments after the 1980 period could be because the channels have stabilised and therefore only bend, bar and width adjustments are observed (Skinner and Haycock, 2004). Similar results were found in Hoaroak Water, Exmoor, UK, where the channel showed relative stability and no major channel planform alteration 25 years after a flood-initiated avulsion (Anderson and Calver, 1980; Werritty and Ferguson, 1980).

The temporal pattern of river planform adjustments is commonly linked to anthropogenic activity (Gilvear and Winterbottom, 1992; Surian and Rinaldi, 2003; Fryirs et al., 2009). Evidence of river straightening, embankments and bank reinforcements are present in the Wasdale catchment (Skinner and Haycock, 2004). Skinner and Haycock (2004), report straightening on Lingmell Beck occurred between the 1860s – 1899, therefore planform adjustments (e.g., boundary and bar adjustments) mapped over the 1860s-1950s could reflect channel recovery to artificial confinement. However, it is difficult to determine the direct impact of anthropogenic activity, as there is not a precise date of when straightening occurred, and the different time intervals between historic sources used to map planform adjustment are not of sufficient resolution to resolve these impacts. Anthropogenic activity and contemporary river management could explain the lack of boundary adjustments observed after the 1980s period in the Wasdale catchment. For example, on Lingmell Beck the contemporary (~25 year ago) construction of embankments restricts 2D lateral adjustment and might explain reaches of relative 2D stability observed after 1995 period (Fig. 5.14) (Skinner and Haycock, 2004). It is also important to recognise that channel modifications often pre-date the earliest available historic maps and channels may still be responding to 'legacy effects' long after cessation of the anthropogenic activity (Wohl, 2015). Consequently, in this context, it is difficult to state whether the threshold for boundary adjustment occurrence is the result of extrinsic controls (flood events, anthropogenic activity) or as a result of endogenic controls (e.g., progressive planform adjustment and gradient changes) that prime the reach before destabilisation (Brewer and Lewin, 1998).

The use of historical sources for river channel change detection are limited by the temporal availability of data and therefore should not be interpreted as a 'reference' or 'base' of channel planform (Ferguson, 1977). Historic maps and air photographs are often a composite of multiple datasets collected over months or years and therefore it is difficult to determine a single date of production, so 2D channel activity is mapped over 'periods', e.g., 1950s - 1980. Furthermore, the analysis of 2D historical channel planform often assumes that there is a linear or continuous change in channel planform between any two historical data comparisons (Lawler, 1993). However, channel planform adjustments can have different responses over different time scales and can be short-lived (intransitive), instantaneous, lagged, cumulative and progressive (Schumm and Lichty, 1965; Chappell, 1983). Therefore, planform adjustments might go unrecorded between two survey dates, or adjustments might be misinterpreted when comparing unequal time periods between available data (Ferguson, 1977). Instead, historical sources provide a useful record to understand how contemporary channel planform has evolved relative to the different dated historical data. This is demonstrated in the Wasdale catchment, where zones of persistent adjustment (e.g., Lingmell Beck) and relative stability (Gable Beck, Over Beck) are identified over the periods of observable data coverage (Fig. 5.14); this is useful to identify areas susceptible to future adjustment.

5.7 Chapter conclusions

This Chapter presents a systematic catchment scale approach for quantifying the spatio-temporal patterns of 2D river planform stability and adjustment in response to exogenic forcing in an upland headwater catchment. The main results of the approach applied in the Wasdale case study show:

1. Marked contrasts were found between the geomorphic characteristics of 2D stable and adjusting reaches. In the Wasdale catchment, stable reaches (n = 464) had a mean channel width of 8 ± 5 m, slope of 0.1 ± 0.08, local catchment area of 3.4 ± 3.3 km^2, valley bottom width of 110 ± 157 m and bankfull unit stream power of 424 ± 260 W m^{-2}. Adjustment reaches (n = 584) had a mean channel width of 11 ± 5.6 m, slope of 0.08 ± 0.07, local catchment area of 4.7 ± 4.1 km^2, valley bottom width of 170 ± 194 m and bankfull unit specific stream power of 325 ± 250 W m^{-2}.

2. The 2D laterally stable reaches were concentrated in confined low stream order channels, whereas unconfined high stream order channels (fourth and fifth order channels) in the floodplain valley transfer zone, were identified as zones of sediment storage (discontinuity) evidenced by a higher frequency of planform adjustments over the 150 year study period.

3. Valley bottom width showed the greatest statistical difference for identifying planform adjustment types in third and fourth order channels and can be used to explain the location of boundary adjustments. This highlights the importance of confinement through the stream order hierarchy in influencing the accommodation space available for planform adjustment and stability.

4. Boundary adjustments were identified in 1860s – 1950s and 1950s – 1980 and coincided with the occurrence of flood-rich periods determined from long-term archival and gauged flood records in the Lake District upland region. After the 1980s no boundary adjustments were observed despite the occurrence of flood-rich periods suggesting the system has either (i) achieved local stability or a new equilibrium, (ii) has not been impacted by a flood of sufficient magnitude, or (iii) has been stabilised by anthropogenic modification restricting lateral adjustment. Further analysis should explore the impact of anthropogenic modification and response of the system to future extreme flood events.

The general methodology developed here can easily be applied to other catchments with commonly available historic maps, air photographs and DTM data. Chapter 6 will apply the methodology developed here to the rest of the Lake District upland catchments to investigate if the spatial patterns and controls of 2D planform adjustments are consistent across multiple catchments in the region, or if they are catchment specific. This will help identify relatively 'active' and 'stable' catchments that will inform a better understanding of sediment continuity, process-form behaviour, and aid with (i) the predictions of where adjustments might occur in the future, and (ii) the identification of locations for management or restoration priorities at a regional level.

Chapter 6

A multiple catchment scale assessment of regional patterns and controls of historic river planform adjustment

6.1 Chapter summary

Multiple-catchment scale assessments of planform adjustments provide the opportunity to understand historic patterns and controls of sediment continuity at the regional scale, which can be used to identify: (i) 'active' and 'stable' catchments, (ii) the dominant controls on planform adjustment, and (iii) evaluate whether patterns and controls of adjustment are catchment specific or similar across a region. This Chapter explores the patterns and controls of planform adjustment and stability across the 17 catchments in the Lake District study region (1250 km^2). Planform adjustment and stability was mapped over six time periods between 1860s – 2010 on 270 rivers and streams (total length 597 km). In total 29,832 stable and adjusting reaches were mapped over all time periods. Between 1860s – 2010, 21% (128 km) of rivers and streams studied were adjusting. Catchments showing persistent patterns of adjustment (Ennerdale and Wasdale) and stability (Haweswater, Kent and Sleddale) were identified. There were marked contrasts between the geomorphic characteristics of stable and adjusting reaches: stable reaches had narrower channel and valley bottom widths (were topographically confined), steeper channel slopes and higher specific stream power values than adjusting

reaches. Large scale adjustments (e.g. avulsions) were longest in engineered channels, as systems adjust to reach a pre-disturbance form, a natural 're-wilding' process.

6.2 Introduction

The aim of this research is to quantify the spatial patterns and geomorphic variables of upland river planform adjustments and stable reaches over the past 150 years at the reach, catchment and multiple catchment scale. Currently, few studies take a rigorous quantitative assessment of planform adjustments from channel headwaters to sink (Lisenby and Fryirs, 2016; Soar et al., 2017), or make comparisons between planform adjustment patterns between multiple catchments in a region over the last 150 years (Wishart, 2004). Hence, this chapter moves beyond reach and single catchment scale assessments of historic planform adjustments to explore catchment variability in sediment continuity and planform adjustment across the 17 catchments in the Lake District study region (Fig. 6.2). The objectives of this chapter are to:

i) quantify the geomorphic characteristics of the catchments and rivers studied in the upland region,
ii) quantify the spatial patterns of planform adjustment across multiple catchments over the past *c.* 150 years, and
iii) use these data to assess if the patterns and controls of channel planform adjustments are catchment specific or consistent across a region.

This chapter begins by outlining the methodology (modified from the method presented in Chapter 5) that is used to analyse planform adjustments across the 17 catchments in the upland study region (Section 6.3). The results are then presented in three parts, the first (Section 6.4) discusses the geomorphic characteristics of the 17 catchments and rivers studied in the upland region (Chapter 6, Objective i). Secondly (Section 6.5), the spatial and temporal patterns of planform adjustments over the last *c.* 150 years (Chapter 6, Objective ii) are discussed. The third section (Section 6.6) discusses the linkages between planform adjustment and geomorphic characteristics to compare catchment to catchment variability (Chapter 6, Objective iii). The results of the three sections are then discussed (Section 6.7).

6.3 Development of methodology

The methodology developed and tested in Chapter 5 (Joyce et al., 2020) is applied on a catchment by catchment basis to the 17 catchments (area 8 - 362 km^2) on channels with a stream order ≥2 in the Lake District study region (Chapter 3). The method involves quantifying catchment and river geomorphic variables (slope, channel width, valley bottom width, catchment area, stream power) extracted from station points (SPs) positioned along the river network and linking them to historic channel planform dynamics in upland catchments (Joyce et al., 2020). The analysis is structured on Strahler's (1952; 1957) stream order to reflect the natural scaling of geomorphic variables: catchment area, channel width, length, slope, stream power and valley bottom width downstream (Leopold and Miller, 1956; Strahler, 1957; Miller et al., 2003; Hughes et al., 2011). In the analysis, a river is classified according to the stream order number.

The workflow presented in Chapter 5 (Joyce et al., 2020) is developed to include an additional data input (land cover map (LCM)) and processing step (creation of map of managed rivers) to assess the impact of land cover type and anthropogenic modifications (e.g. engineered structures) on planform stability (Fig. 6.1). These controls are better assessed at the regional scale where variations in land cover and anthropogenic activity are likely to show greater contrasts between catchments (Rowland et al., 2017; Verstraeten and Prosser, 2008). Figure 6.1 summarises the modified workflow.

In Part 2 of the workflow, the LCM is introduced to provide an indication of vegetation coverage (Fig. 6.1). Catchment-wide and riparian vegetation can influence sediment availability and river bank stability, which can influence the potential for planform adjustment (Millar, 2000; Crosota and Saleh, 2011; Vargas-Luna et al., 2019). The Corine LCM is used as it provides a full spatial coverage of the upland study region at 25 m resolution (Rowland et al., 2017). Despite the coarse resolution of the LCM, it provides a generalised overview of the main land cover types appropriate in a regional scale analysis that can easily be imported into GIS. The LCM is categorical data and therefore is extracted at planform adjustment locations in Part 3 of the methodology (Fig. 6.1).

In assessing river channel stability, it is important to identify managed channel reaches to assess if sediment continuity and planform adjustment patterns differ to unaffected river reaches (Brookes, 1988; Sear et al., 2000; Downs and Gregory, 2004; Gregory, 2019). In the workflow, an additional processing step 'creation of map of rivers managed' is added to capture channel modifications (Fig. 6.1). The term 'managed' is defined here as sections of river that have been modified (i.e. channelized), maintained, reinforced, dredged or regulated. A generalised map of managed rivers in a catchment can be developed using:

- Historical maps and air photographs to identify features such as wall structures, embankments, presence of bridges and bridge reinforcements in and along the channel.
- The Environment Agency (EA) asset management and flood protection structures database (Environment Agency, 2019). These databases locate current river assets that are managed to prevent flood risk or to improve habitat diversity and therefore can indicate modified river sections.
- Archival sources including newspapers, river board authority reports and the database of river restoration schemes (Black and Law, 2004; RRC, 2018). These reports document historical and recent channel works.
- River Habitat Survey database (Raven et al., 1997; Environment Agency, 2019b). This database provides an indication of artificial modification to channel morphology through 'habitat modification score', by documenting the presence or absence of artificial features.

Managed reaches are mapped as a polyline feature along the river network so that the total length of rivers managed can be calculated. The map of managed rivers therefore represents an estimate of the extent of channel modification and it is likely that more rivers will have been historically managed, which is difficult to identify without detailed field investigation or local knowledge. In Part 3 of the methodology (Fig. 6.1), planform adjustment types are categorised as occurring in 'managed' channels if they overlay a stretch of the channel that has been mapped as managed. If a planform adjustment or stable reach overlays part managed and natural reach, they are assigned 'semi-natural' category. The map of managed rivers represents the cumulative impact of river management, rather than temporal trends in management i.e. it is a summary of both historic and contemporary channel modifications on a river.

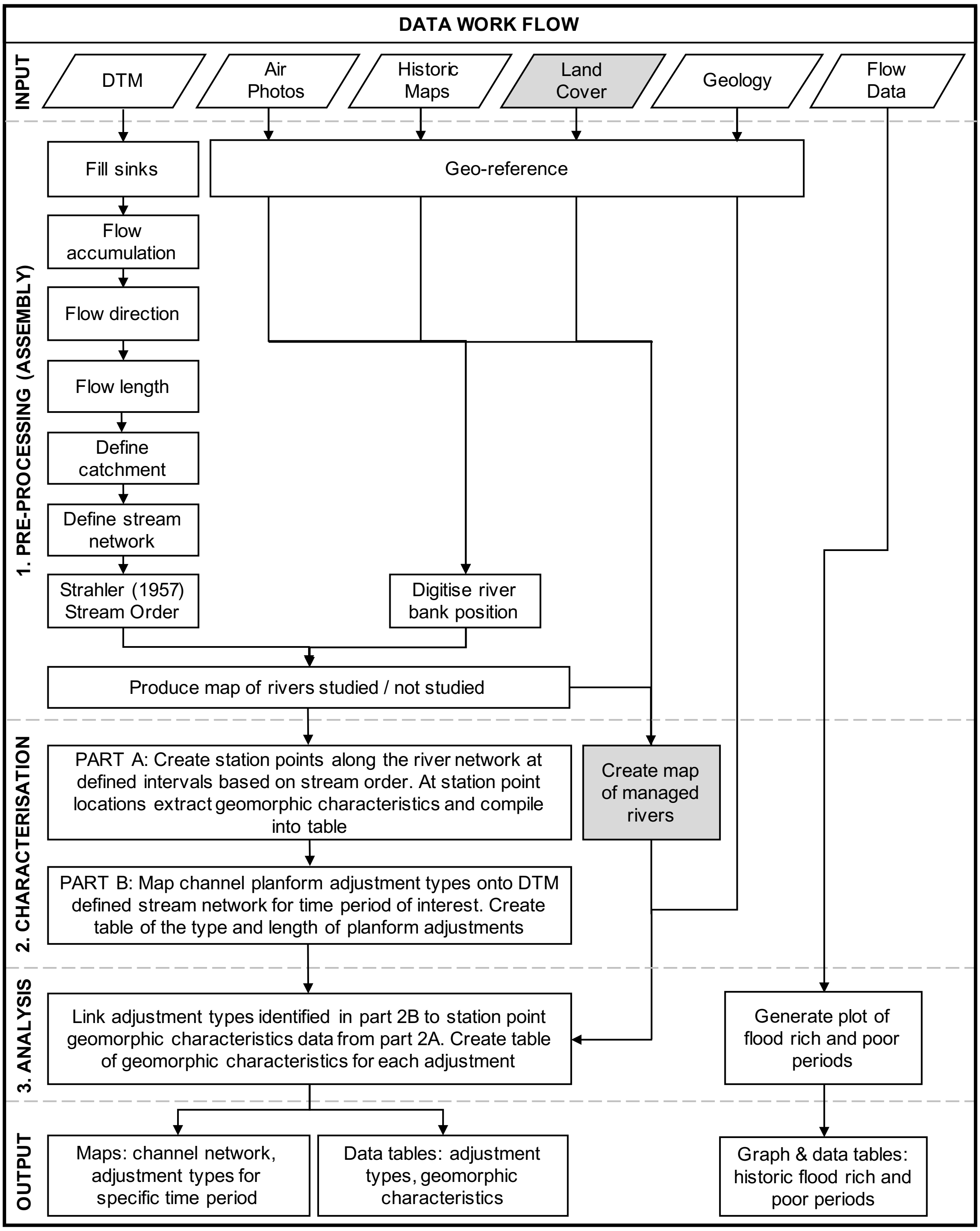


Figure 6.1. Data requirements and GIS workflow for identifying and analysing planform adjustments, stable reaches and geomorphic variables. The workflow is adapted (grey shaded boxes) from the version in Figure 5.1 (Chapter 5) as it includes LCM data input, and creation of map of managed rivers in Part 2.

6.3.1 Data pre-processing

Data was pre-processed following the steps in Figure 6.1, on a catchment by catchment basis. Air photographs and historic maps for the 17 catchments were geo-referenced in GIS for planimetric accuracy, using >8 hard-edged ground control points (GCPs) and a second order polynomial transformation (Hughes et al., 2006; Donovan et al., 2015; Donovan et al., 2019). Across the 17 catchments studied there was a decrease in the root mean square error (RMSE) from the 1860s historic map (mean RMSE 2.6 ± 1.2 m) to the 2010 air photograph (mean RMSE 0.70 ± 0.25 m), (Table 6.1). Although scale differences and geo-referencing errors exist between historic maps and air photographs, the datasets provide a valuable record of river planform at the catchment scale over a period of the last *c.* 150 years.

Table 6.1. RMSE geo-referencing errors for historic maps and air photographs used in the analysis.

	RMSE (m) of historic maps and air photographs					
Catchment	**1860s**	**1950s**	**1980**	**1995**	**2004**	**2010**
BASSENTHWAITE	5.12	6.56	0.47	1.14	1.05	0.68
CALDER	1.68	1.36	1.47	1.19	1.05	0.46
CALDEW	1.37	2.84	1.64	1.04	0.80	0.40
CAWDALE	1.65	1.68	0.58	1.36	0.91	0.80
CONISTON	4.11	1.81	1.81	0.52	0.62	0.80
CRUMMOCK	1.40	2.41	1.69	0.30	0.92	0.33
DUDDON	2.01	1.81	2.76	1.64	1.02	1.09
ENNERDALE	4.88	3.67	4.67	1.20	1.00	0.99
ESK	2.99	3.58	2.45	1.01	0.92	0.88
HAWESWATER	1.12	1.18	2.11	0.46	0.81	1.00
KENT	3.13	2.18	1.50	0.44	0.72	0.75
SLEDDALE	1.45	2.06	0.12	0.88	0.35	0.29
SPRINT	2.14	2.02	0.57	1.09	1.01	0.47
SWINDALE	2.63	3.03	0.83	1.53	1.65	1.00
ULLSWATER	3.81	3.65	3.43	0.63	0.18	0.63
WASDALE	2.60	3.30	1.50	1.40	0.80	0.80
WINDERMERE	2.16	4.52	2.24	0.49	0.71	0.56
Mean	**2.60**	**2.80**	**1.76**	**0.96**	**0.86**	**0.70**
Std. Dev.	1.24	1.35	1.16	0.42	0.32	0.25

6.4 Regional geomorphic characteristics

This section presents and discusses the geomorphic characteristics across the 17 catchments in the Lake District upland study region derived from Part 2A of the methodology (Fig. 6.1). Geomorphic characteristics, slope, valley bottom width, stream power, river length, channel width and catchment area are expected to be related to stream order, according to the basic laws of catchment geometry (Leopold and Miller, 1956; Gordon et al., 2004). Understanding the geomorphic characteristics by stream order between the 17 catchments will help interpret the patterns of planform adjustment identified in Part 2B of the methodology (Fig. 6.1). Section 6.4.1 firstly summaries the rivers and catchments studied, which is followed by a discussion of the between catchment variability in geomorphic characteristics in Section 6.4.2.

6.4.1 Summary of rivers and catchments studied

In total, 270 rivers and streams (total length 597 km) were studied across the 17 catchments (8 – 362 km^2) in the Lake District upland study region (total area 1250 km^2), (Fig. 6.2). Table 6.2 summaries the catchment area, number of rivers studied, total length of rivers studied, area of lakes and the number of SPs for each catchment. The Bassenthwaite catchment is the largest catchment (361.8 km^2), with the most rivers (n = 55) studied (Table 6.2). The largest waterbodies in the Bassenthwaite catchment are Bassenthwaite Lake (5.2 km^2), Derwent Water (5.2 km^2), and Thirlmere Reservoir (3.3 km^2) which act as long term sediment sinks. The smallest catchments studied were Cawdale (8 km^2), which has no major waterbodies, and Sleddale (12 km^2) where the rivers discharge into Wet Sleddale Reservoir (area 0.31 km^2), (Table 6.2).

The geomorphic variables (channel width, valley bottom width, slope, specific stream power and catchment area) were extracted and calculated at 1359 SP locations across the study region. The mean density of SPs for second, third, fourth, fifth and sixth order channels was 4, 6, 8, 4 and 4 respectively. A lower density of station points was observed in fifth and sixth order channels as the river lengths were shorter (Table 6.3) as they are truncated by the presence of downstream waterbodies.

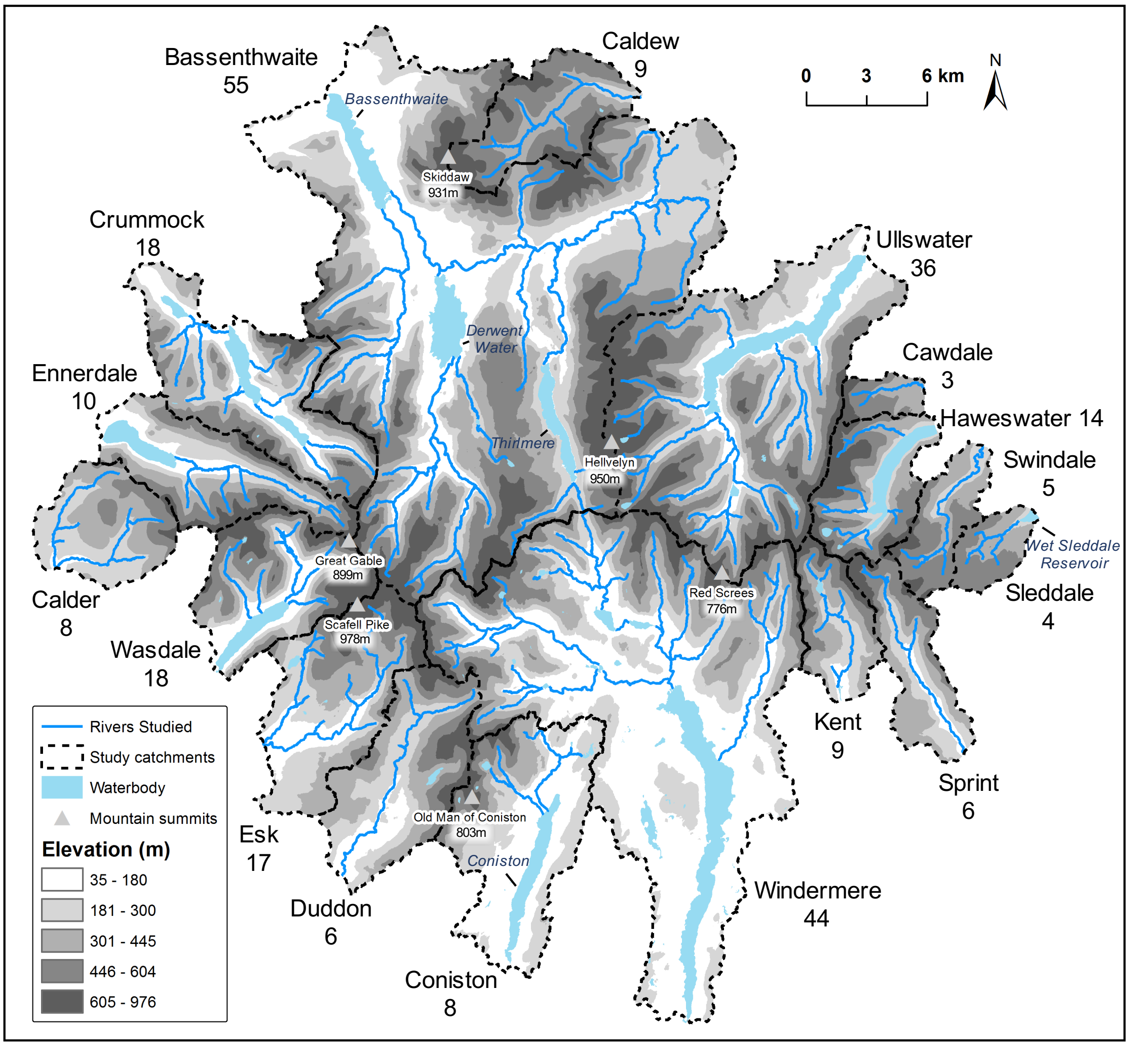


Figure 6.2. The Lake District upland study region showing the topography, the catchments and rivers studied. Numbers indicate the total number of rivers studied in each catchment.

Catchment geometry 'laws' (Horton, 1945; Leopold and Miller, 1956; Selby, 1985) state that as channel stream order increases the mean number of streams, channel slope and specific stream power decreases, and the mean stream length, catchment area, valley bottom width and channel width increases. Figure 6.3 and Table 6.3 summarise the mean geomorphic characteristics extracted at each of the station points for each stream order to explore the stream order scaling laws across the study region.

Table 6.2. Catchment area, number and total length of rivers, area of waterbodies and number of station points for the rivers and catchments studied in the Lake District upland study region.

Catchment Name	Catchment area (km^2)	Number of rivers studied	Total length of rivers studied (km)	Total waterbody area (km^2)	Number of station points
BASSENTHWAITE*	361.8	55	171.2	14.01	348
WINDERMERE	239.8	44	99.4	17.76	213
ULLSWATER	146.6	36	73.6	9.48	163
CONISTON	63.2	8	14.8	5.2	37
CRUMMOCK*	62.5	18	33.7	4.1	94
ESK	54.6	17	32.0	0.29	73
DUDDON	50.0	6	16.9	0.26	33
WASDALE*	45.4	18	24.0	2.94	63
ENNERDALE*	44.1	10	22.5	3.02	61
CALDEW	33.9	9	20.2	0.03	50
HAWESWATER*	32.5	14	16.4	4.09	54
CALDER	31.4	8	19.7	-	49
SPRINT	27.7	6	14.4	-	27
KENT*	22.4	9	12.6	0.43	30
SWINDALE	19.1	5	13.04	0.002	27
SLEDDALE*	11.6	4	7.3	0.31	21
CAWDALE	7.8	3	5.3	-	16

** indicates catchments with lakes with water abstraction and downstream flow regulation*

Of the 270 rivers studied, 134 (50 %) were second order channels, 96 (35 %) were third order channels, 29 (11 %) were fourth order channels, 9 (3 %) were fifth order channels and 2 (1 %) were sixth order channels, (Table 6.3). Mean channel length increases by a factor of 4 from second to fourth order channels, ($R^2 = 0.99$), (Table 6.3, Fig. 6.3). However, fifth and sixth order channels show a decrease in channel length, because lakes truncate the downstream extent of the channel, for example, in Bassenthwaite, Ullswater, Wasdale and Windermere catchments (Table 6.3, Fig. 6.2). The presence of lakes therefore explains the overall weak relationship ($R^2 = 0.37$) observed between stream order and mean river length in the Lake District upland region (Fig. 6.3).

The R^2 value is greater than 0.9 for mean valley bottom width, channel width, slope, catchment area, specific stream power when plotted on a semi-log graph against stream order, agreeing with the expected catchment scaling laws (Leopold and Miller, 1956; Gordon et al., 2004), reflecting the longitudinal variation in the upland catchment stream order hierarchy (Fig. 6.3). For example, from second to sixth order channels mean local channel slope decreases by a factor of 100, specific stream power decreases by a factor of 24, channel width increases by a factor of 9, mean valley bottom width increases by a factor of 26, and local catchment area increases by a factor of 69 (Table 6.3).

There are interrelationships between the geomorphic characteristics studied (Fig. 6.4). For example, in the upland setting it is expected that as slope decreases catchment area, channel width and valley bottom width will increase and specific stream power will decrease downstream (Leopold and Miller, 1956; Gordon et al., 2004). Figure 6.4 explores the interrelationships between the geomorphic variables extracted at the SPs for all rivers and streams studied. Valley bottom width and channel width show the most scatter compared to the other variables (Fig. 6.4). For example, as catchment area increases it is expected that channel width will increase in response to the larger contributing area (Leopold and Miller, 1956), however, this is not a linear relationship and channels with large channel widths (e.g. >40 m) are recorded as having small (<50 km^2) catchment areas (Fig. 6.4). One explanation of this is because of anthropogenic modification to river channel width. Channels can be widened or narrowed to stabilise the river, increase capacity and protect homes and infrastructure, therefore changing the natural downstream geometry laws (Knighton, 1998). Similarly, valley bottom width shows scatter when compared to channel width and catchment area (Fig. 6.4). This scatter, again, could be attributed to anthropogenic activity influencing channel width or is related to local variability in catchment hypsometry influenced by the geological and glacial legacy which creates wider U-shaped valleys. The relationship between channel and valley width in Figure 6.4 could also indicate underfit streams which have undergone a drastic reduction of discharge following deglaciation or flow regulation and are now relatively small for the valleys they occupy (Dury, 1964; 1968). Identifying anomalies in the relationships between geomorphic variables is useful for interpreting planform adjustment patterns.

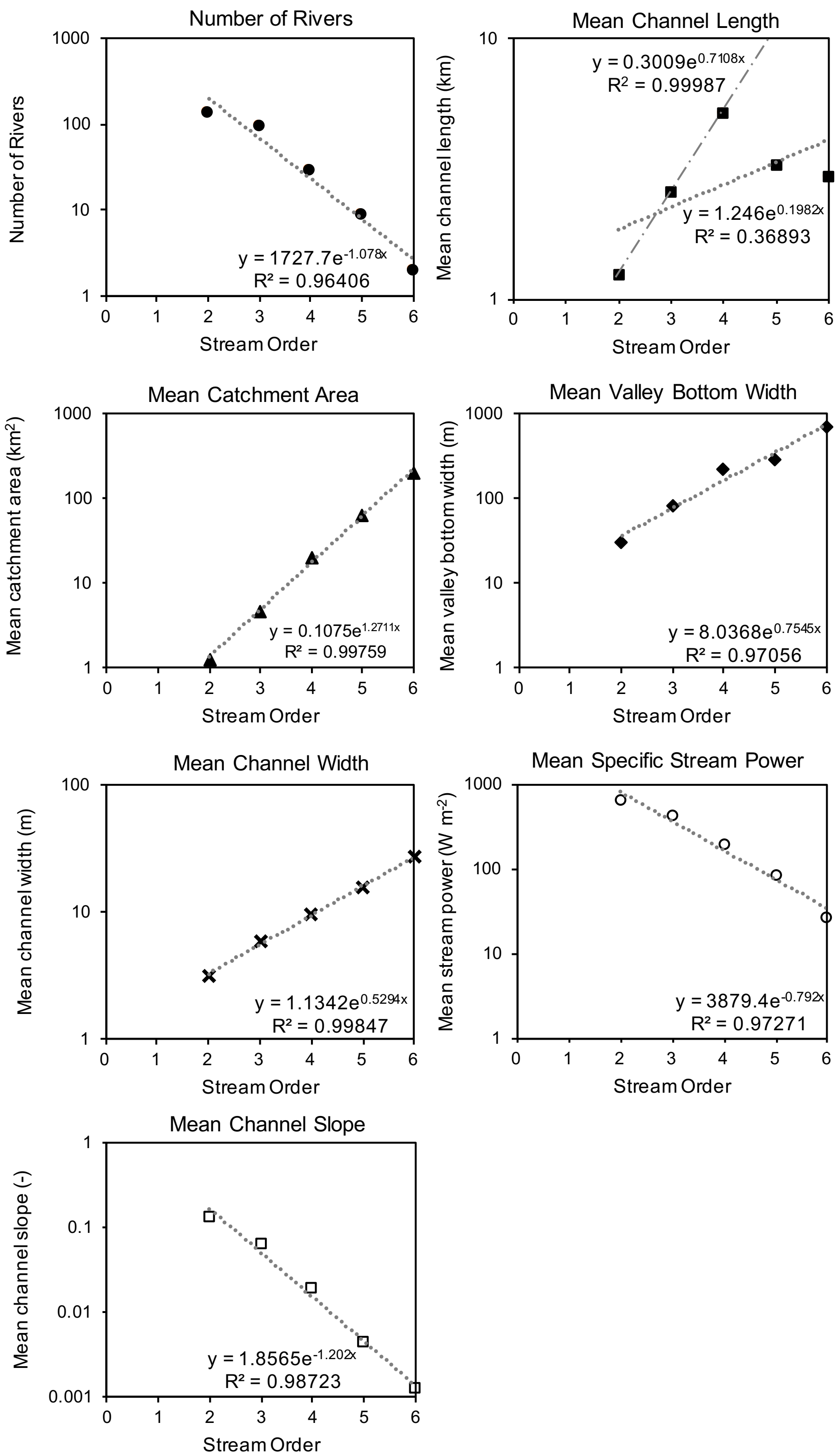


Figure 6.3. Mean geomorphic characterises extracted at the station points of the 270 rivers and streams studied in the Lake District study region plotted against stream order. Two regressions are plotted on mean channel length: the dotted line is the overall regression for the Lake District study region, the dashed regression line shows relationship of second to fourth order channels mean length (e.g. without the impact of waterbodies on channel length). Mean values and standard deviations are reported in Table 6.3.

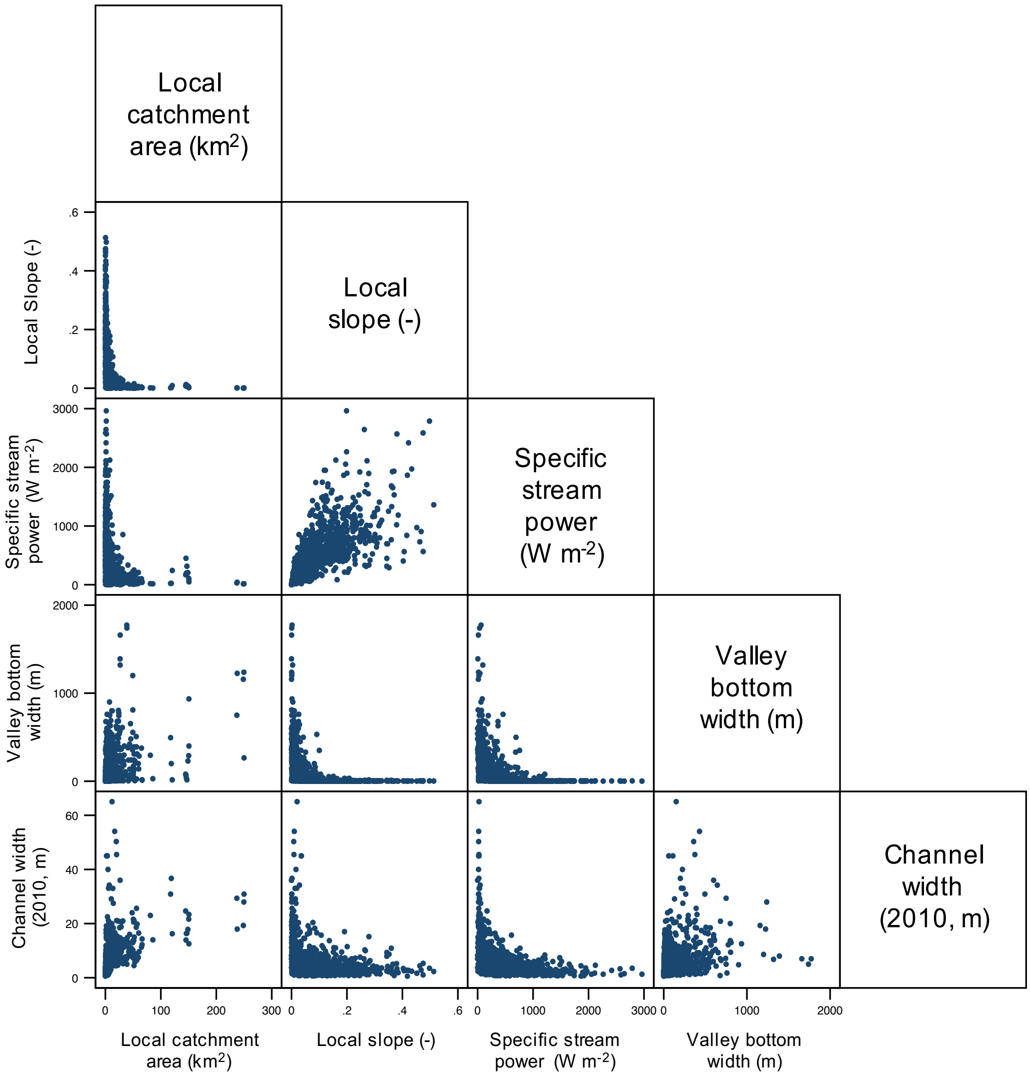


Figure 6.4. Matrix plot showing interrelations between geomorphic variables extracted at the station points in the Lake District study region.

This section has presented an overview of the geomorphic characteristics across all 17 catchments studied in the Lake District. The mean geomorphic characteristics follow the expected stream order scaling laws (Leopold and Miller, 1956; Gordon et al., 2004). However, the presence of lakes in the upland sediment cascade disrupts the scaling pattern between channel length and stream order (Fig. 6.3). The interrelationships between the geomorphic variables (Fig. 6.4) highlighted that there is a not a clear relationship with valley bottom width, channel width or catchment area downstream. This can be explained by anthropogenic activity which can modify channel width or by variations in catchment hypsometry influencing valley bottom width. The next section discusses the variability in the geomorphic characteristics between the 17 catchments in the study region.

Table 6.3. Mean geomorphic characteristics extracted at the station points for each stream order in the Lake District study region.

Stream Order	Number of river studied	Number of Station Points (SP)	Channel Length (km)		Slope (-)		Local Catchment Area (km^2)		Valley Bottom Width (m)		2010 Channel Width (m)		Specific Stream Power ($W\ m^{-2}$)	
	Total	*Total*	*Mean*	*Std. Dev.*	*Mean*	*Std. Dev.*	*Mean*	*Std. Dev.*	*Mean*	*Std. Dev.*	*Mean*	*Std. Dev.*	*Mean*	*Std. Dev.*
2	134	555	1.2	0.8	0.129	0.098	1.3	0.9	27	70	3	3	629	430
3	96	535	2.6	2.0	0.063	0.064	4.7	3.4	84	127	6	5	421	386
4	29	221	5.1	3.0	0.019	0.028	20.3	13.6	225	289	10	6	196	235
5	9	40	3.3	2.6	0.004	0.003	63.8	43.8	290	260	16	5	84	94
6	2	8	3.0	3.4	0.001	0.001	201.3	60.8	716	439	27	6	27	13

6.4.2 Between catchment variability in geomorphic characteristics

This section compares the geomorphic characteristics between the 17 catchments studied. This is achieved by looking at statistically significant differences between the geomorphic variables extracted at the SPs between the catchments through one-way ANOVA and Tukey (HSD) tests (as discussed in Chapter 5). A description of the results of this analysis is presented for each geomorphic variable in Sections 6.4.2.1 – 6.4.2.5 and data tables of statistical differences are collated in Appendix C. Differences between catchment geomorphic variables are used to explain the spatial patterns of planform adjustment and stability.

6.4.2.1 Local slope

Slope influences the energy of a river and potential for sediment erosion, transfer and deposition and therefore planform adjustment (Knighton, 1998). Slope decreases through the stream order hierarchy, the box plots (Fig. 6.5) display the range of slope values by catchment. The mean channel slopes are steepest in the Haweswater (0.14 ± 0.11), Wasdale (0.13 ± 0.11), and Ennerdale catchment (0.11 ± 0.09). The lowest mean channel slopes were observed in the Duddon (0.04 ± 0.06), Caldew (0.05 ± 0.03) and Calder (0.06 ± 0.03) catchments.

According to the stream order scaling laws (Leopold and Miller, 1956; Gordon et al., 2004), (Fig. 6.3), mean slope values will differ between the stream orders (Leopold and Wolman, 1956; Gordon et al., 2004). One-way ANOVA showed statistical significant differences were present between second (p-value 0.000), third (p-value 0.000) and fourth (p-value 0.026) order channel mean slope values between all catchments. However, no statistical differences were found between mean slope values between fifth (p-value 0.948) and sixth (p-value 0.1835) order channels. This could be due to a fewer number of fifth and sixth order channels surveyed (Table 6.3), or the presence of lakes interrupting the stream order scaling.

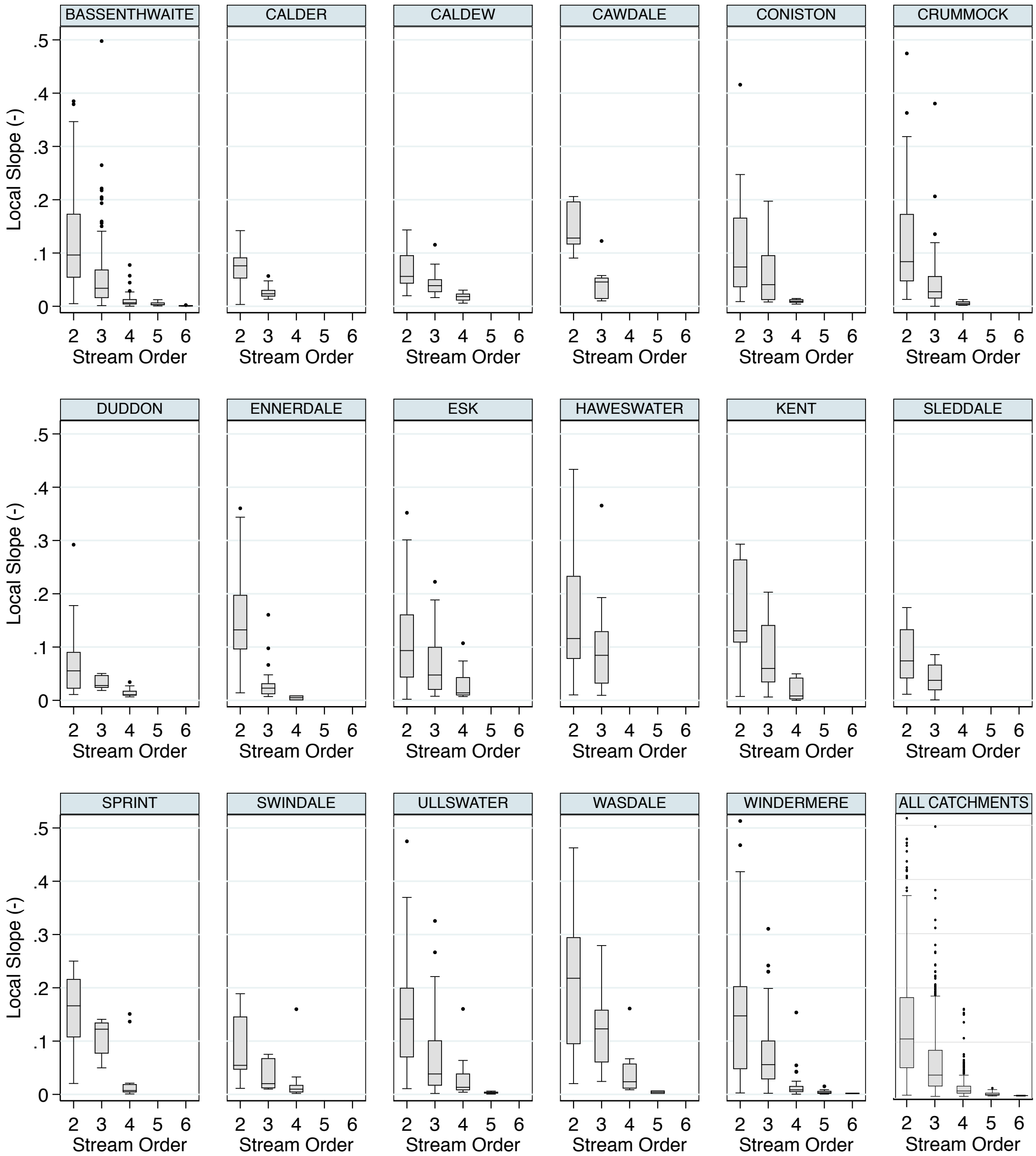


Figure 6.5. Box plots showing local slope (-) extracted at each SP across the stream order network for each catchment in the Lake District study region.

The Wasdale catchment had the highest number of statistical differences ($n^* = 7$) in mean slope values in second order channels compared to the other catchments. There were fewer statistical differences identified between third order channel mean slope values across the catchments ($n^* = 6$), 5 of these statistical differences were identified between the Wasdale catchment due to a larger range of third order slope values (0.02 – 0.28) compared to the other catchments (Fig 6.5). Haweswater and Calder catchments also showed statistically significant differences between third order mean channel slope values.

Calder had the lowest mean slope values (0.02 ± 0.002) in third order channels, whereas Haweswater had some of the steepest channel slopes (mean 0.09 ± 0.007). In fourth order channels statistical differences in mean channel slopes were identified between the Wasdale and Bassenthwaite catchment.

The statistical analysis highlights that there are differences in channel slope between stream order and the catchments studied. The Wasdale and Haweswater catchments stand out and are characterised as having relatively steep channel slopes in comparison to the other catchments. Conversely, the Calder catchment has the lowest mean channel slopes compared to the other catchments (Fig. 6.5). Variability in slope will influence sediment continuity therefore it is expected that planform adjustment and stability will differ between catchments that have steeper and shallow channel slopes (Knighton, 1998; Richards, 1982).

Catchment relief ratio (R_r) was calculated after Schumm (1956) to explore the variability in catchment slope between the 17 catchments studied in the Lake District:

$$R_r = \frac{h}{L} \quad (1)$$

where h is the difference between the elevation at the outlet of the catchment and the highest point on the drainage divide and L is the maximum length of the catchment, R_r is dimensionless. The catchment relief ratios (Table 6.4) show the Wasdale (0.101) and Cawdale (0.108) catchments are the steepest catchments. In contrast the Bassenthwaite (0.034), Windermere (0.034) and Crummock (0.044) have the lowest relief ratios, these catchments have multiple valleys separated by lakes representing both upland and lowland valley systems, explaining the lower relief ratios (Table 6.4, Fig. 6.2).

6.4.2.2 Local catchment area

Catchment area influences the amount of water that flows into rivers (Knighton, 1999). Figure 6.6 displays the variability in local catchment area extracted at the SPs for each stream order and catchment. The general pattern shows that catchment area increases as stream order number increases, as expected with stream order scaling (Gordon et al., 2004; Hughes et al., 2011), (Fig. 6.6). The Bassenthwaite and Windermere catchments have the largest range of catchment areas 0.1 – 250 km^2, these are the only catchments with sixth order channels studied. In contrast, the Sleddale, Calder and Cawdale catchments have the smallest range of mean catchment areas across the stream order hierarchy (0.2 – 17 km^2), only second and third order channels are studied in these catchments.

However, the pattern is not linear in all catchments as the relationship between catchment area and stream order is related to catchment hypsometry (Fig. 6.6; Table 6.3). Catchment hypsometry describes variations in catchment shape and elevation, this is determined by geological controls (e.g. resistance to erosion), and glacial ice extents which influence the shape and size of valleys (Stone et al., 2010). Therefore, it is expected that statistical differences will exist between stream order and catchment area between the catchments. One-way ANOVA showed statistically significant differences between the mean catchment areas for each stream order between the 17 catchments (p-value for second, third, fourth and fifth order channels = 0.000, p-value for sixth order channels = 0.0087). In second order channels n* = 24, in third order channels n* = 30, in fourth order channels n* = 12, in third order channels n* = 3 and in fourth order channels n* = 1. Overall, the highest number of statistical differences between stream order and catchment areas were identified between the Bassenthwaite, Calder, Caldew, Crummock, Wasdale, Ennerdale and all other catchments.

The analysis highlights that there are statistically significant differences in catchment area between the 17 catchments studied. To explore this relationship further the form ratio (R_f) was calculated for the 17 catchments after Horton (1932):

$$R_f = \frac{A}{L^2} \tag{6.1}$$

where A is catchment area (km^2) and L is the maximum length of the catchment (km).

Catchments with smaller form ratios will be narrower and elongated compared to catchments with high form ratios. The form ratio in elongated catchments is often indicative of the flood-regime of the river (Horton, 1932). In the Lake District study region, elongated catchments identified were Sprint, Ennerdale, Crummock and Swindale (Table 6.4). In contrast, the Wasdale and Calder catchments display an irregular or bowl like shape (higher form ratio), these catchments show statistical differences in catchment area. In irregular and bowl shaped catchments form-ratio is not a sensitive indicator of the hydrologic characteristics (Horton, 1932). This analysis highlights that catchment area and shape varies considerably across the upland region and therefore hydrologic regime, and channel behaviour is likely to vary between catchments (Table 6.4).

Table 6.4. Catchment area, maximum catchment length, form ratio, relief ratio and highest stream order for the 17 catchments studied in the Lake District upland region.

Catchment	Catchment Area (km^2)	Maximum Length (km)	Form ratio	Relief ratio	Highest stream order
BASSENTHWAITE	361.8	26	0.54	0.034	6
WINDERMERE	239.8	25	0.38	0.034	6
ULLSWATER	146.6	17	0.51	0.046	5
CONISTON	63.2	13	0.4	0.058	4
CRUMMOCK	62.5	16	0.24	0.044	4
ESK	54.6	10	0.55	0.081	4
DUDDON	50	11	0.41	0.063	4
WASDALE	45.4	9	0.56	0.101	5
ENNERDALE	44.1	14	0.22	0.048	4
CALDEW	33.9	10	0.34	0.070	4
HAWESWATER	32.5	8	0.47	0.077	3
CALDER	31.4	7	0.64	0.074	3
SPRINT	27.7	11	0.22	0.058	4
KENT	22.4	8	0.34	0.083	4
SWINDALE	19.1	8	0.3	0.060	4
SLEDDALE	11.6	6	0.36	0.054	3
CAWDALE	7.8	4	0.49	0.108	3

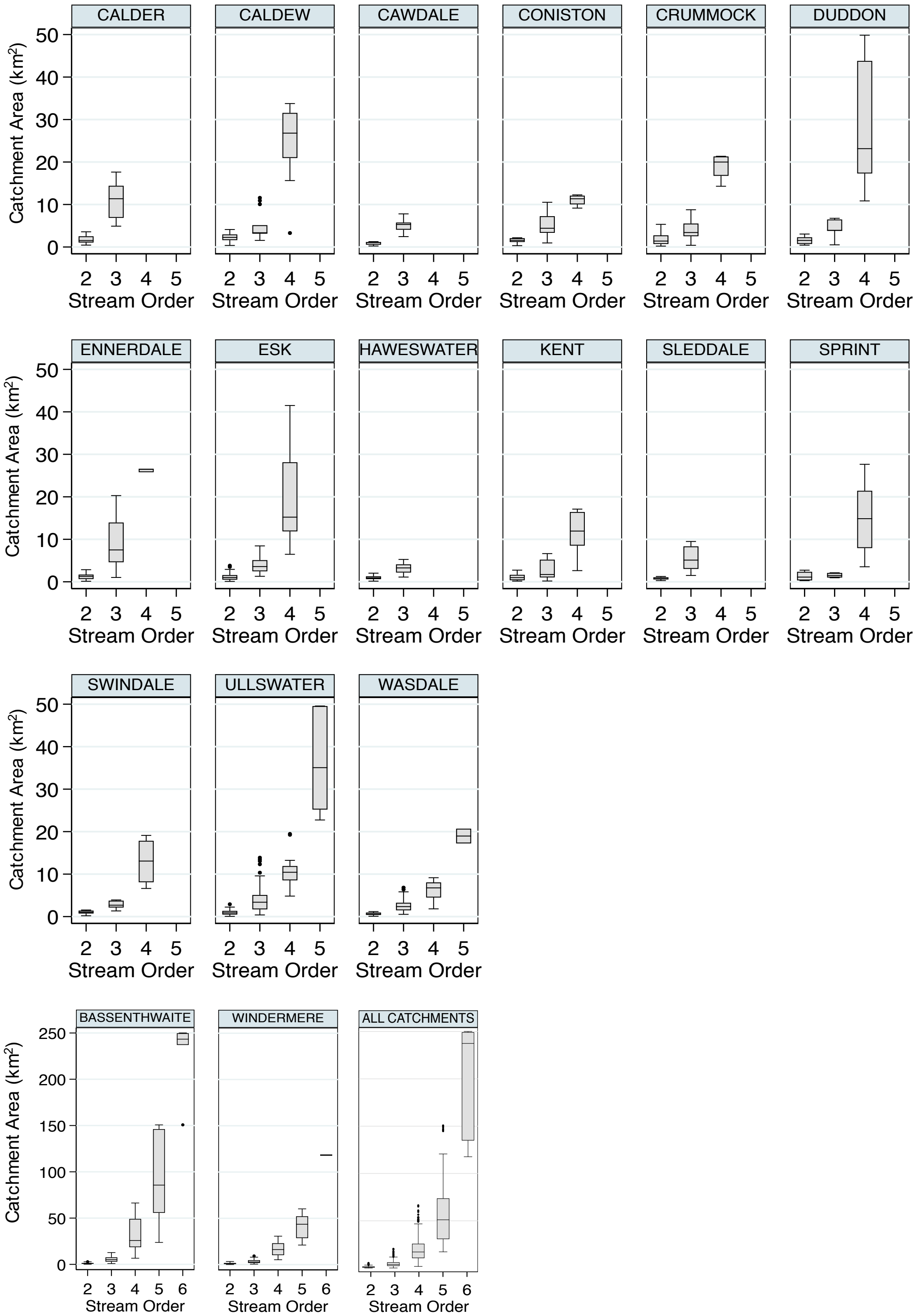


Figure 6.6. Box plots showing range of catchment area values extracted at each SP across the stream order network across the 17 catchments in the Lake District study region. The Bassenthwaite, Windermere and all catchments box plots have been plotted on different axes as these have the largest range of catchment areas.

6.4.2.3 Valley bottom width

Valley bottom width is determined by the geological and glacial history which set the catchment shape and floodplain extent (Wilson, 2010; Evans and McDougall, 2015). Valley bottom width determines the accommodation space available for the channel to migrate laterally, and therefore influences sediment continuity (Schumm, 1977; Church, 1996; Fryirs et al., 2016; O'Brien et al., 2019; Joyce et al., 2020). In topographically confined headwaters lateral adjustments are less likely, in contrast where the valley bottom width increases planform adjustments are expected. There is variability in valley bottom width between the 17 catchments (Fig. 6.7). The catchments with the largest valley bottom widths in the Lake District study region are the Duddon (150 ± 145 m), Sprint (150 ± 95 m) and Bassenthwaite (140 ± 260 m) catchments. In contrast, the narrowest mean valley bottom widths were measured in the Calder (60 ± 40 m), Haweswater (70 ± 50 m) and Coniston (80 ± 90 m) catchments. It is therefore expected that these catchments will display different patterns planform adjustment and stability over the past 150 years.

Mean valley bottom width increases by a factor of 4.5 from second to sixth order channels in the Lake District study region (Table 6.3). Figure 6.7 shows the variability in valley bottom widths against stream order by catchment. Second order channels typically have narrow valley bottom widths (mean 27.4 ± 70 m), however, there are some outliers, and large valley bottom widths are observed in these channels, representing local floodplain pockets and may represent local sedimentation zones (e.g. in the Bassenthwaite, Esk, Wasdale, Sprint catchments), (Fig. 6.7). Fourth and fifth order channels have the largest variability in channel width (range in fourth order channels, 4 – 1770 m, range in fifth order channels: 6.8 - 935 m), (Fig. 6.7).

The Bassenthwaite catchment has some of the largest valley bottom widths observed through the stream order hierarchy compared to the other catchments studied (Fig. 6.7). For example, mean valley bottom width in second order channels is 20 ± 76 m and in sixth order channels is 839 ± 433 m in the Bassenthwaite catchment (Fig. 6.7). The Bassenthwaite catchment represent a complex-multi valley setting (with both upper and lower zones of the upland sediment cascade) with multiple lakes and lowland areas downstream of Keswick (Fig. 6.2). Therefore, the simple downstream geometry laws in the Bassenthwaite catchment are less applicable. In catchments with wide valley bottom widths it is expected that there is accommodation space for lateral planform adjustment and sediment deposition.

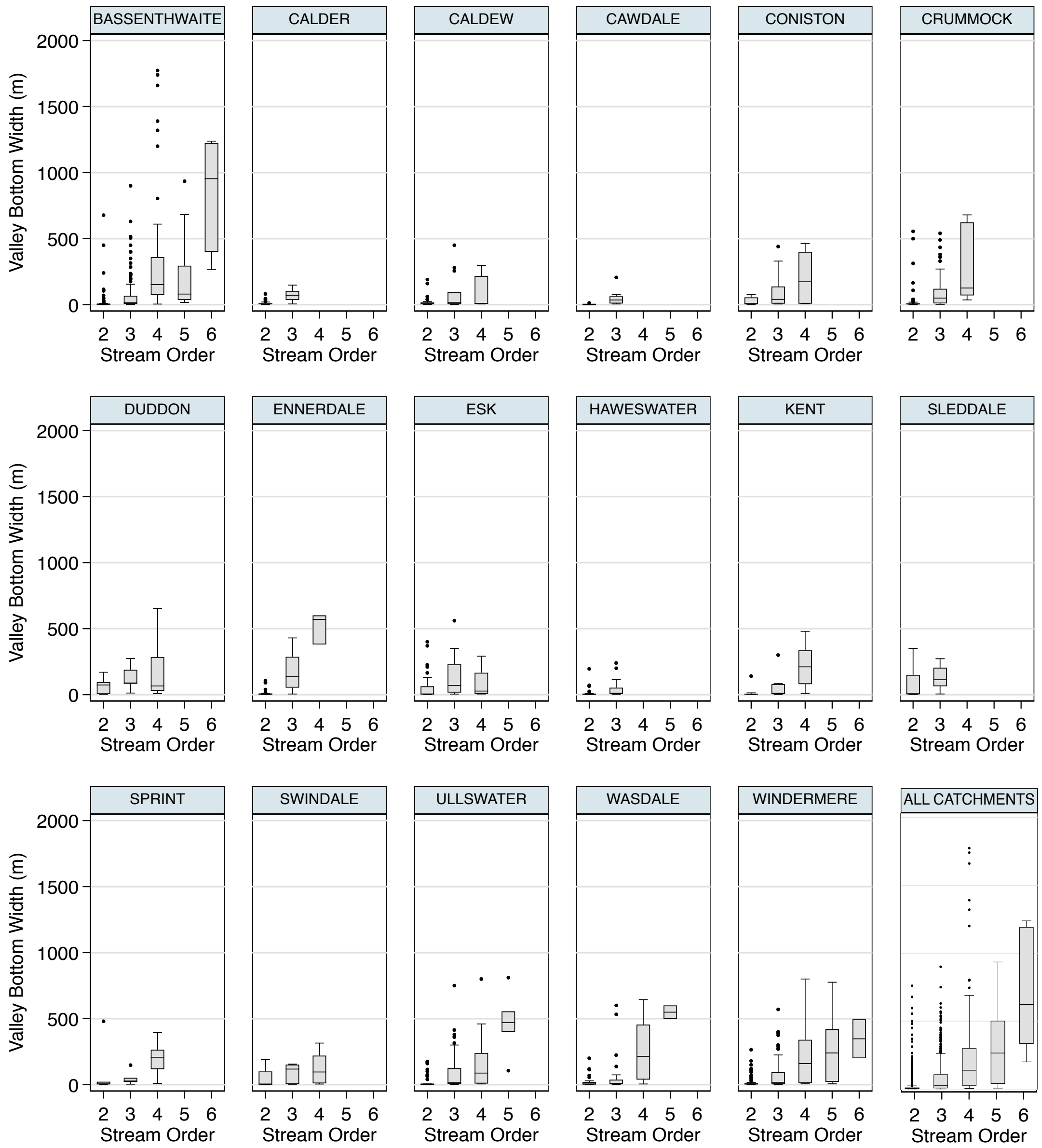


Figure 6.7. Box plots showing the range of valley bottom width values extracted at each SP across the stream order network for the 17 catchments studied in the Lake District study region.

One-way ANOVA was performed to see if there were statistically significant differences between valley bottom width and stream order. Statistically significant differences were recorded between second order valley bottom widths regionally (p-value 0.0141). But subsequent Tukey (HSD) analysis did not highlight any significant differences between valley bottom widths between catchments for stream orders ≥3. One-way ANOVA showed no statistical differences between mean valley bottom widths for third (p-value 0.1482), fourth (p-value 0.0647), fifth (p-value 0.0973) and sixth order channels (0.1874). Therefore, the pattern of valley bottom width is relatively consistent through the stream order hierarchy between catchments in the study region despite variability in river network pattern and catchment shape (Fig. 6.2, Table 6.4).

6.4.2.4 Channel width

Channel width (measured from the 2010 air photograph) increases with stream order across the catchments studied (Fig. 6.3, Table 6.3) as expected downstream (Leopold and Wolman, 1956). The mean widest channel were observed in the Ennerdale (10 ± 12 m) and Coniston (8 ± 9 m) catchments, the mean narrowest channels were observed in the Haweswater (4 ± 2 m) and Cawdale (3 ± 3 m) catchments. Figure 6.8 displays the range of channel widths by stream order and catchment.

One-way ANOVA highlighted statistical differences between stream order and channel width between the catchments (second order p-value = 0.000, third order p-value = 0.0000, fourth order p-value = 0.0023, fifth order p-value = 0.0006); as expected with the stream order scaling laws (Leopold and Wolman, 1956; Gordon et al., 2005). No statistical differences were identified between mean channel width values in sixth order channels, likely due to the low frequency of rivers studied here (n = 2).

In second order channels, 16 statistical differences in mean channel width were identified between the Coniston and other catchments. Second order channels in the Coniston catchment had a mean channel width of 8 ± 11 m, this is a factor of 3 greater than the mean width of second order channels observed in the other 16 catchments studied (Fig. 6.8). Large channel widths were measured in second order channels near Coniston Copper Mines (NGR SD 289 985) where the channel flows through spoil heaps and sediment is directly delivered to the channel. This is discussed in further detail in Section 6.7. Hence, second order channel widths are disturbed by reach scale anthropogenic activity explaining the statistical differences.

In third order channels, 19 statistically significant differences were identified between the catchments mean channel width. The highest number of statistically significant differences in channel width between the catchments were observed in the Ennerdale catchment (n* = 16). The Ennerdale catchment has relatively low human impact with few river channel constraints. Therefore, third order channels in the Ennerdale catchment could migrate laterally and interact and erode river banks contributing to the formation of sediment bars in the channel. Third order channels in the Ennerdale catchment had a mean channel width 20 ± 15 m, this is a factor of four greater than the mean width of third order channels observed in the other catchments studied. Statistical differences were also observed in third order channels between the Bassenthwaite and Calder, Calder and Ullswater, and Ullswater and Coniston catchments.

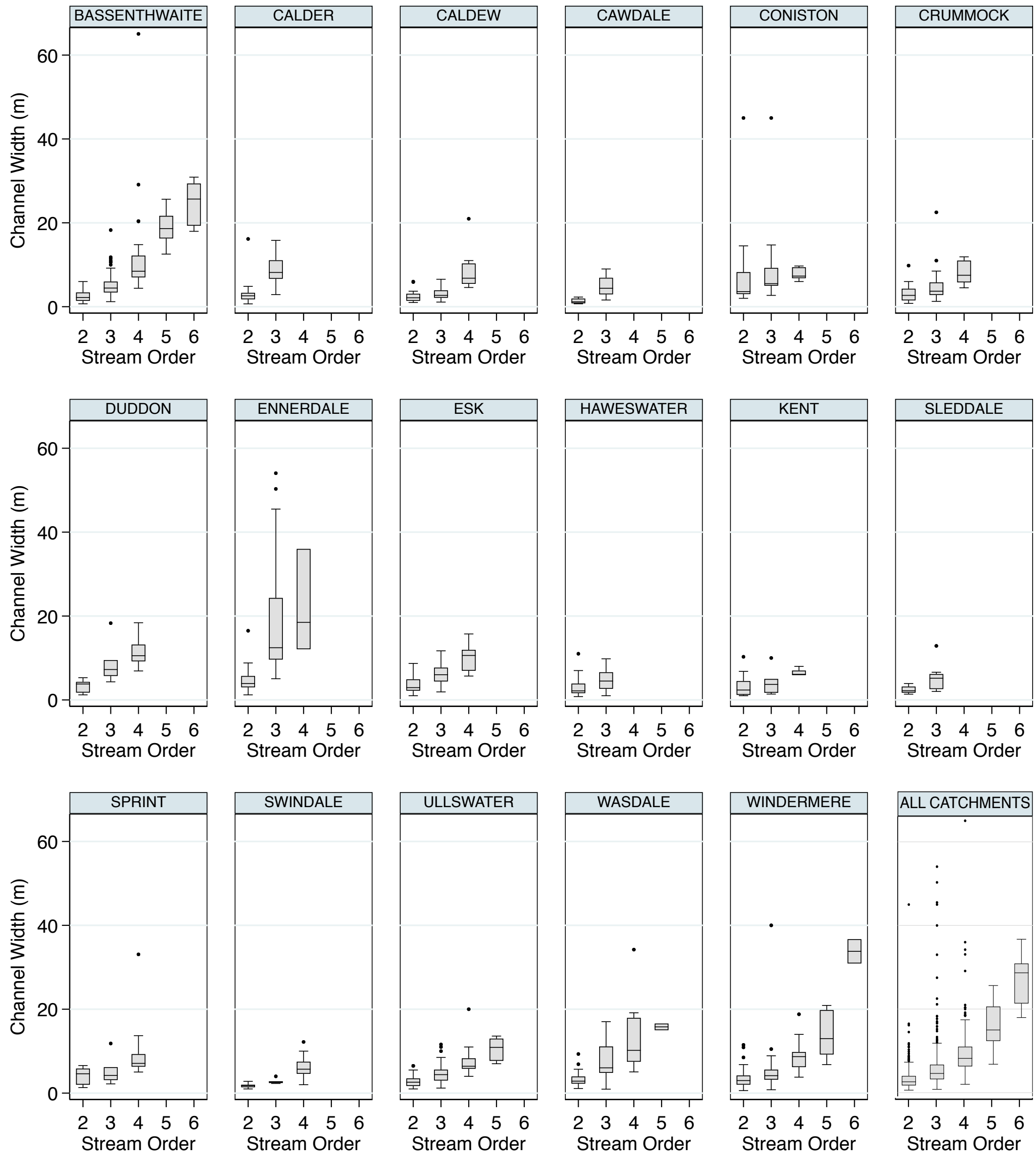


Figure 6.8. Box plots showing channel width (2010) variability by stream order and catchment across the Lake District study region.

Eight statistically significant differences were identified between catchment channel widths in fourth order channels in the Ennerdale catchment. Mean channel width in fourth order channels was 22 ± 12 m in the Ennerdale catchment, this is double the mean channel width observed in fourth order channels in the other study catchments. Fifth order channels had 2 statistically differences observed between Bassenthwaite, Ullswater and Windermere catchments. However, the smaller number of statistical differences identified in fourth and fifth order channels could be due to a fewer number of fourth, fifth channels surveyed across the 17 catchments (Table 6.3).

The analysis highlights that channel width scales with stream order, however there is local variability between the 17 catchments. For example, the Ennerdale and Coniston catchments have some of the largest channel widths studied (Fig. 6.8). This is attributed to anthropogenic activity in the Coniston catchment (mining) and natural channel-bank and floodplain interactions (low anthropogenic modification) in the Ennerdale catchment.

6.4.2.5 Unit specific stream power

Specific stream power defines the energy expenditure through a river system and therefore can be used as a diagnostic for understanding the patterns of sediment transfer, erosion and deposition (Bagnold, 1966; Baker and Costa, 1987; Knighton, 1999; Thompson and Croke, 2013; Marchi et al., 2016; Martínez-Fernández et al., 2019). Mean unit specific stream power decreases through the stream order hierarchy from 628 ± 430 W m^{-2} in second order channels to 27 ± 13 W m^{-2} in sixth order channels (Table 6.3). The highest specific stream power values were measured in the Cawdale catchment (900 ± 600 W m^{-2}), (Fig. 6.9), this catchment had the narrowest mean channel widths (Fig. 6.8). The Sprint (300 ± 260 W m^{-2}) and Duddon (250 ± 200 W m^{-2}) catchments had the lowest mean specific stream power values. The Duddon catchment had one of the lowest mean slope values (Fig. 6.5). It is therefore expected that these catchments will display different patterns of planform adjustment and stability. For example, in catchments with lower specific stream powers, sediment deposition is expected resulting in a higher frequency of in-channel bars.

One-way ANOVA identified statistically significant differences in second order channels (p-value 0.000) and third order channels (p-value 0.0015) specific stream power values across the catchments studied (Fig. 6.9). In second order channels, the highest number of statistical differences between specific stream order values were identified between Cawdale and the other 16 catchments studied (n* = 13). Mean specific stream power in second order channels was highest in Cawdale (1294 ± 366 W m^{-2}) compared to the other catchments (Fig. 6.9). In third order channels, 3 significant differences in specific stream power were identified between Calder and Haweswater, Ennerdale and Haweswater, and the Ennerdale and Windermere catchments. Third order channels in the Ennerdale catchment had a lower, narrow range of specific stream power values (mean specific stream power 128 ± 126 W m^{-2}, Fig. 6.9) compared to the other catchments. No statistically significant differences were identified in specific stream power between fourth, fifth or sixth order channels across the study region. This analysis shows there is catchment variability in specific stream power values (Fig. 6.9), which will influence sediment continuity and therefore the potential for planform adjustment and stability. The relationship between specific stream power and planform adjustment will be explored further in Section 6.6.

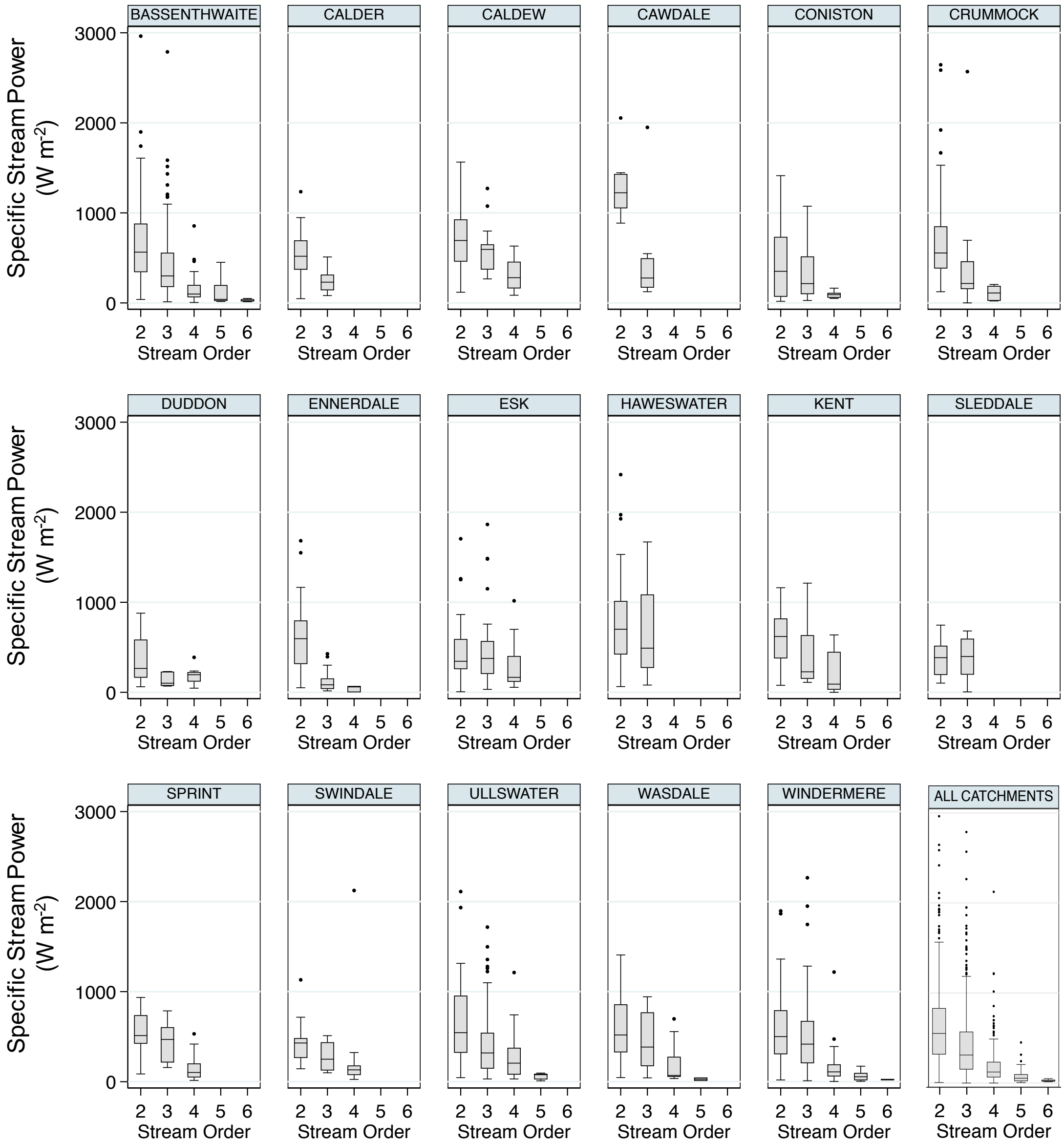


Figure 6.9. Unit specific stream power variations by catchment and stream order calculated at the station points in the study region.

6.4.2.6 Bedrock and superficial geology

Geology partly controls the availability, type and erodibility of sediment and therefore influences the potential for planform adjustment (Schumm, 2005). Chapter 3 summarises the main bedrock and superficial geologies for the Lake District upland region. This section describes the bedrock and superficial geologies between the 17 catchments studied. It is important to consider the spatial variability in geology across the region as this will influence the patterns of planform adjustment and stability mapped over the last *c.* 150 years (Section 6.6).

The bedrock structural geology determines the Lake District radial drainage pattern (Mill, 1895). The Borrowdale Volcanics are the dominant bedrock geology in the central Lake District upland study region (Stone et al., 2010; Wilson, 2010) and therefore all of the catchment headwaters studied begin in the Borrowdale Volcanics geological zone. Igneous Borrowdale Volcanics dominate the bedrock geology coverage in the Duddon (97 %), Wasdale (93 %) and Cawdale (90 %). The Caldew (81 %), Crummock (80 %) and Bassenthwaite (60 %) catchments are dominated by the Skiddaw group and erodible sedimentary rocks (Figs. 6.10). The Ennerdale catchment is dominated (47 %) by the Ordovician felsic plutonic intrusion into the Skiddaw Group and the Borrowdale Volcanic Group and comprises of medium-grained resistant granophyric granite and microgranite, with zones of diorite, dolerite and hybridised rocks (British Geological Survey, 2016). The Kendal group is the dominant bedrock geology in the Sprint (40 %) catchment comprising of erodible siltstone, mudstones and sandstones (Fig 6.10), (British Geological Survey, 2016). The bedrock geology was eroded by glacial activity during the Quaternary, creating U-shaped valleys and over-depended glacial troughs (Wilson, 2010; Evans and McDougall, 2015), which determines the drainage pattern, channel slope and valley bottom width. The influence of bedrock geology on planform adjustment and stability will be discussed further in Section 6.6.

The spatial variability in superficial geology is important for understanding the types of sediment in upland channels and the potential patterns of planform adjustments (Knighton, 1998). Figure 6.11 summarises the superficial geologies across the Lake District region, where superficial geology is not present it indicates the presence of bedrock outcrops (British Geological Survey, 2016). The Coniston catchment has the lowest percentage coverage (24 %, Fig. 6.11) of superficial geology indicating that this catchment is dominated by bedrock outcrops of the Coniston group slates, Borrowdale Volcanics and erodible sedimentary rocks of the Kendal group (Fig. 6.10). In contrast, the Cawdale catchment has the highest percentage of the catchment area (79 %) covered by superficial geologies (Fig. 6.11), this was the smallest catchment studied (Table 6.2).

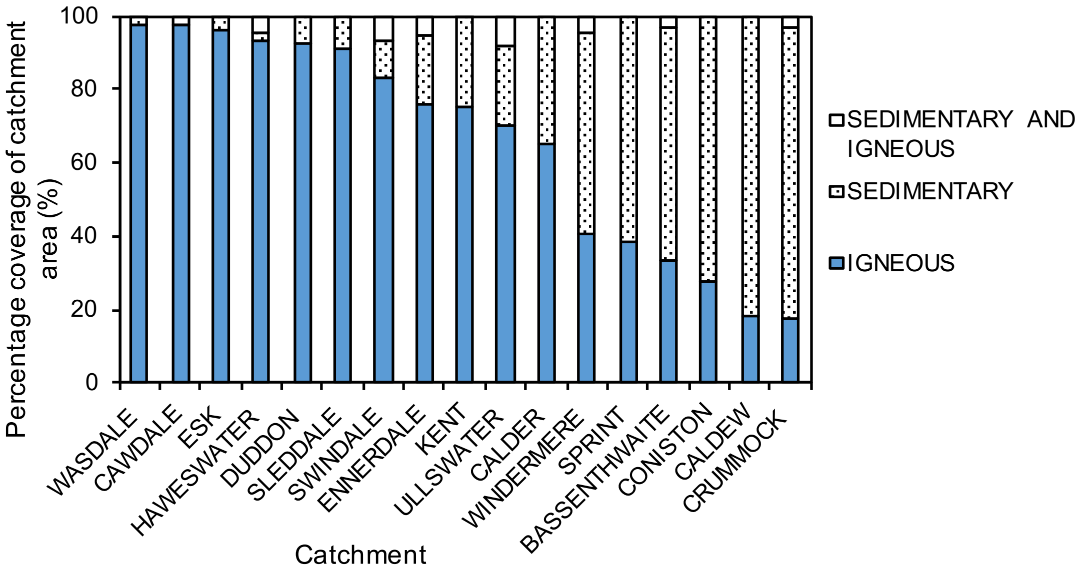


Figure 6.10. Bedrock geology sedimentary and igneous classes by catchment in the Lake District study region (data source: British Geological Survey, 2015).

Glacial deposits (diamicton, clay sand, gravel) are the most frequent superficial geology observed across the Lake District study region (Fig. 6.11) reflecting the glacial legacy (Wilson, 2010; Evans and McDougall, 2015). Glacial sediments contribute mixed sized sediments to the channel, which are re-worked during daily flows and flood events. Organic deposits (peat) coverage is largest in Sleddale (41 %), Swindale (27 %), and Caldew (25 %) catchments (Fig. 6.11). Peat erosion has been shown to be an important influence on sedimentation in gravel-bed rivers and narrow peatland streams (Evans and Warburton, 2001) therefore in peat catchments (e.g. Sleddale) it is expected that in-channel sediment deposition and bar formation will occur, which can cause local increases in channel width.

Mass movements (landslip, talus, head and dry valley deposits) are most frequent in the Ennerdale (17 %) and Wasdale (14 %) catchments (Fig. 6.11). If mass movements are coupled to the channel they will provide a source of sediment and influence planform adjustment (Harvey, 1991; Harvey, 2001). The Ennerdale catchment has the highest percentage of mass movements, if these mass movements are connected to the channel they can contribute to in-channel sedimentation, which locally redirects flows to the bank causing bank erosion, explaining the large channel widths recorded (Fig. 6.8). For example, Figure 6.12 shows the variability in channel widths extracted at the SPs and superficial geology types across the 17 catchments. In the Ennerdale catchment channel widths are largest in fluvial sediments (19 ± 15 m), and second largest where mass movements are present (6.4 ± 3 m). Therefore, catchment scale geologies may be useful for interpreting channel characteristics and planform adjustment and stability. However, at the regional scale bedrock and superficial geologies are highly varied and therefore are expected to be a poor discriminatory variable for planform adjustment.

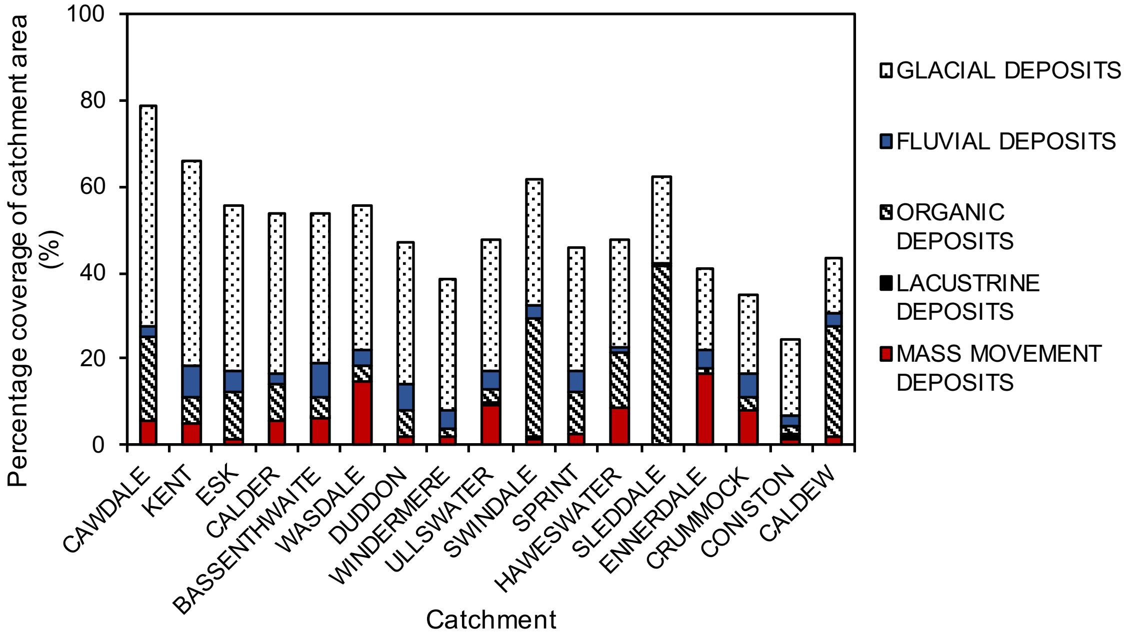


Figure 6.11. Superficial geology by catchment in the Lake District study region (British Geological Survey, 2016). Total percentages are <100% as superficial deposits are not present where the bedrock geology is exposed.

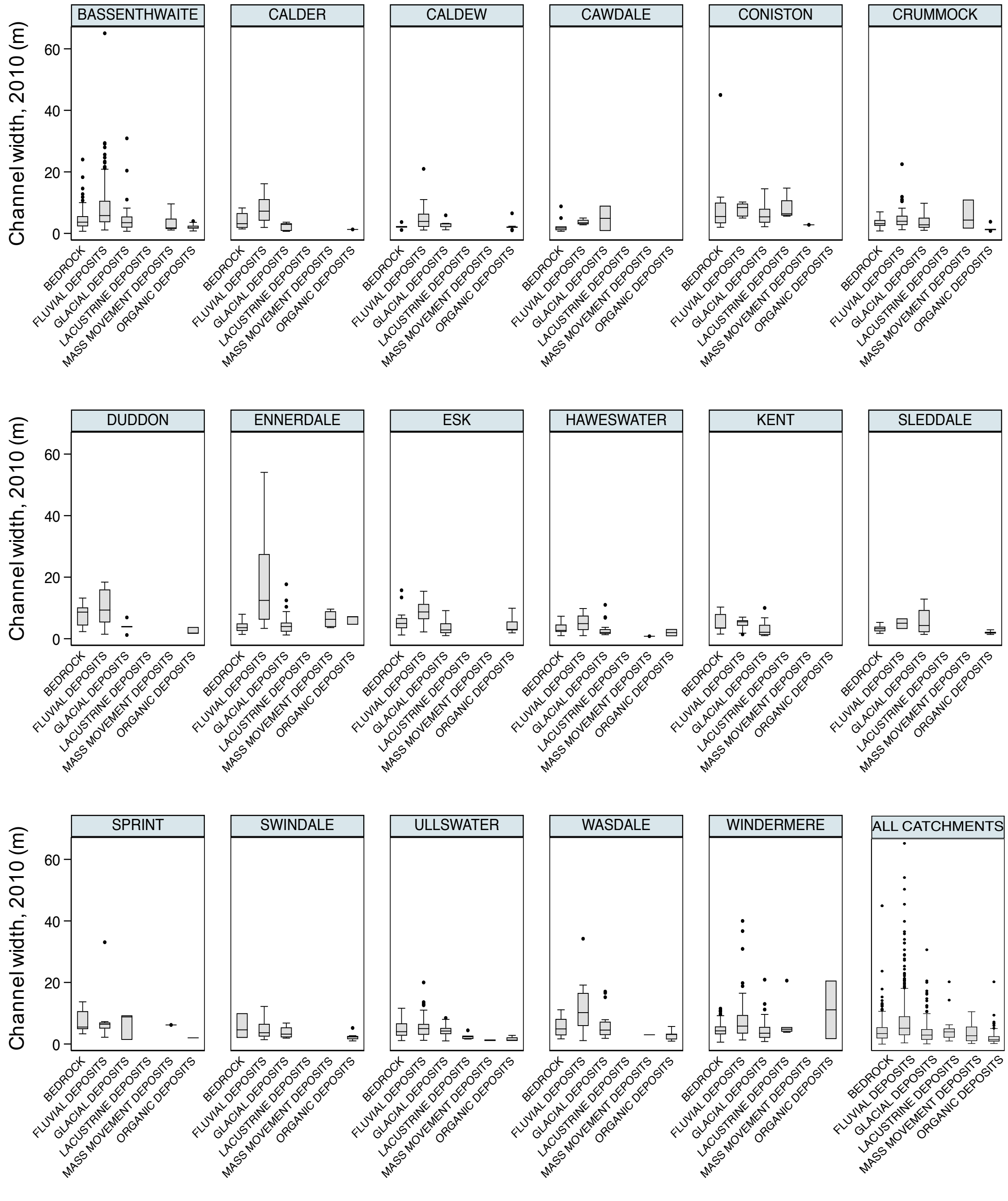


Figure 6.12. Channel width and superficial geology type extracted from the SPs for the 17 catchments studied.

6.4.2.7 Land cover

Land cover influences surface runoff and sediment availability in a catchment, and therefore the potential for adjustment (Millar, 2000; Crosota and Saleh, 2011; Vargas-Luna et al., 2019). For example, in woodland dominated catchments, it is expected that there will be low sediment yields and relative channel stability due to cohesion of surface sediments by tree roots (Hey and Thorne, 1986; Gurnell, 2014). Land cover is a categorical variable and is extracted at planform adjustment locations in Part 3 of the methodology, therefore this section describes the land covers across the 17 catchments studied (Fig. 6.13). The dominant land covers across the Lake District upland study region are acid grassland (60 % coverage, 750 km^2), improved grassland (14 % coverage, 180 km^2), and broadleaf woodland (7 % coverage, 95 km^2), (Fig. 6.13). Due to the low percentage of woodland coverage a high rate of sediment delivery to the channels is expected (Chiverrell, 2006; Hatfield and Maher, 2009).

Vegetation in the riparian zone increases bank stability, and catchment wide vegetation helps to reduce sediment delivery from catchment hillslopes and therefore major adjustments are not expected in forested catchments (Hey and Thorne, 1986; Gurnell 2014). The coarse resolution (25 m) of the LCM means riparian vegetation might not be captured in the LCM, however, this dataset provides a generalised overview of the main land cover types appropriate in a regional scale analysis. Broadleaf and coniferous woodland occupy the largest areas in the Ennerdale (23 %), Windermere (23%) and Coniston (22 %) catchments (Fig. 6.13). Therefore, it was expected that these catchments would have the narrowest channel widths. However, in the Ennerdale and Coniston catchments some of the largest channel widths were observed (Fig. 6.8) suggesting that there are other factors influencing channel stability (e.g. sediment supply, anthropogenic activity) in these catchments. For example, in the Coniston catchment, large channel widths were measured in second order channels near Coniston Copper Mines (NGR SD 289 985) where the channel flows through spoil heaps and sediment is directly delivered to the channel. In the Ennerdale catchment, the wide channel planform pattern was established (1860s) prior to rewilding and coniferous tree planting which began in the late 1920s evidenced in the Ordnance Survey historic maps. Therefore, rewilding and woodland coverage in the Ennerdale catchment does not have a significant impact on channel widths.

Upland peat catchments have been reported as some of the most actively eroding catchments (Stott, 1997; Evans et al., 2006), this may contribute to high river sediment yields and planform adjustment in these catchments (Fig. 6.13). Heather percentage coverage is highest in the Caldew (33 %) and Sleddale (22 %) catchments, these catchments have managed moorlands and a high percentage of organic deposits. Heather catchments were associated with the narrowest channel widths (5 ± 3 m) in the Lake District. Suburban areas are present across the region however, are largest in the lower floodplain valley in the Bassenthwaite (1 %) and Windermere (3 %) catchments and will have a local impact on planform adjustment and stability (Fig. 6.13). Rivers in suburban areas are likely to have a legacy of management to protect homes and land from flooding (Wohl, 2015). Channel management will therefore influence river stability, for example, reinforced river banks and flood protection walls will disconnect the channel from floodplains and prevent lateral planform adjustment. Therefore, it is expected that bar adjustments will be frequent forms of adjustment in suburban areas and only during extreme events will large scale boundary adjustments be observed. The following section discusses river management across the 17 catchments.

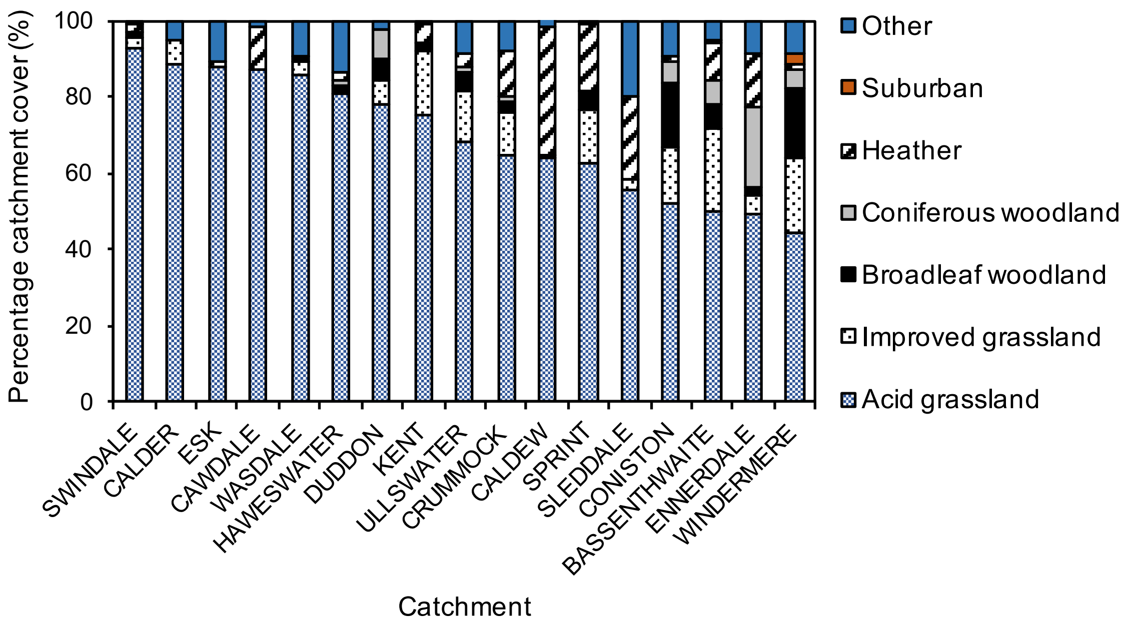


Figure 6.13. Land cover type by catchment in the Lake District study region (Data source: Rowland et al., 2017). The other category includes: freshwater, urban, inland rock, fen marsh and swamp, arable and horticulture, bog and represent less than 20% of the total catchment area.

6.4.2.8 Managed rivers

Figure 6.14 displays the spatial pattern of rivers managed in the Lake District study region. The total length of managed rivers is 200 km, approximately 33 % of the total length of rivers studied. The pattern and extent of rivers managed is likely to be an underestimate as river modifications are poorly documented and difficult to identify from remote sensed data.

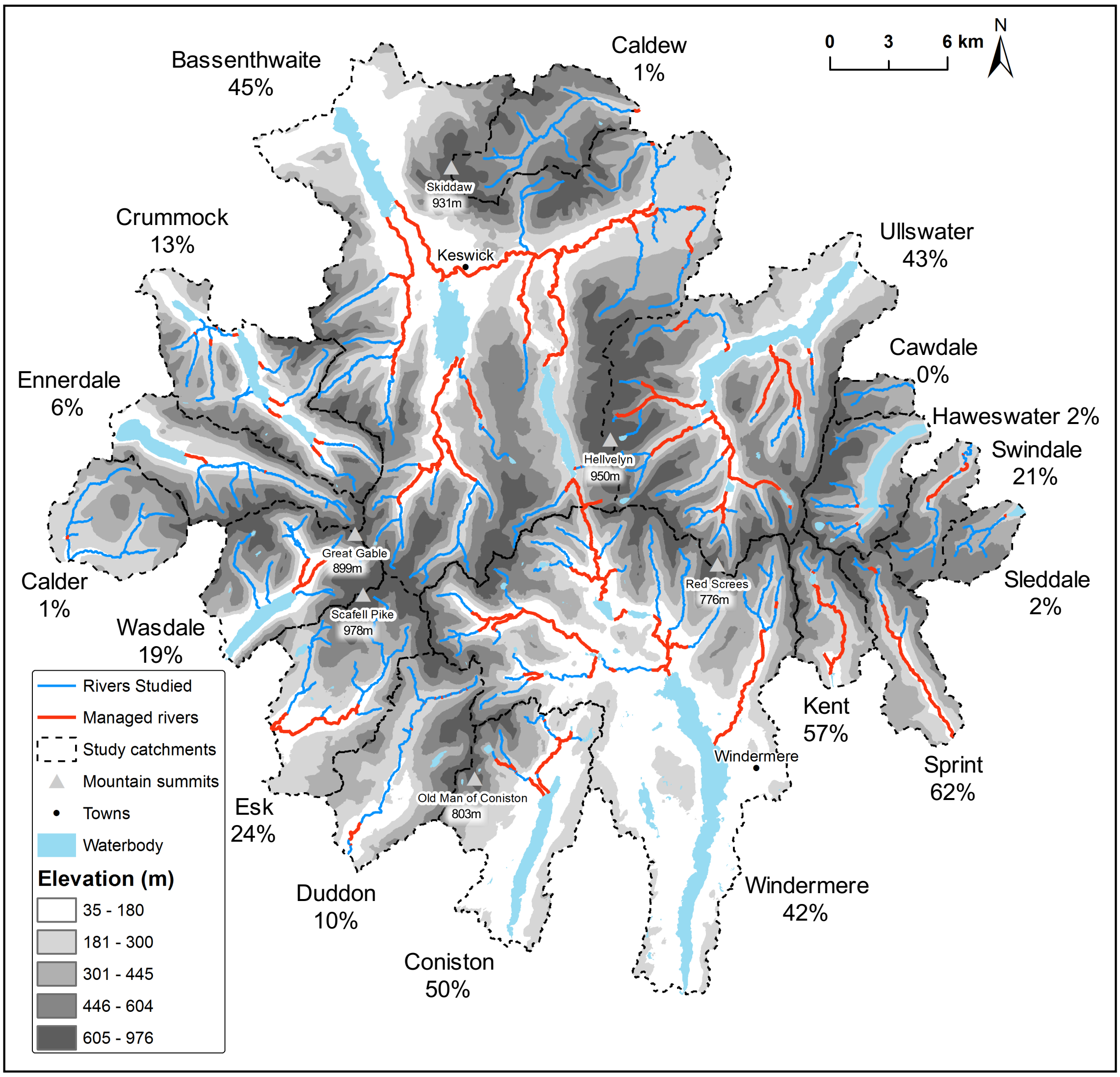


Figure 6.14. Estimated percentage of river channel length managed for the 17 catchments in the Lake District study region.

There is regional and catchment scale variability in river management (Fig. 6.14). The Sprint catchment has the highest percentage (62 %) of channels mapped as managed. In the Sprint catchment, the channels have been resectioned and there is evidence of flood embankments in the historic maps and air photographs. In the lower Bassenthwaite catchment, 45 % of the river length studied is mapped as managed, this is a result of channel realignment, resectioning, bank reinforcement, flood protection structures and flow regulation from reservoirs (e.g. Thirlmere). River management in the Bassenthwaite catchment aims to protect homes and infrastructure from flooding. In contrast, Ennerdale, Calder, Caldew and Cawdale catchments have the lowest percentage of rivers mapped as managed. For example, in Ennerdale 6 % of channel lengths are mapped as managed (Fig. 6.14), this is due to the presence of reinforced banks and structures (e.g. bridges) across the channel.

The mean percentage of channel length mapped as managed increases through the stream order network across all catchments (Fig. 6.15). The mean percentage of channel length mapped as managed in second order channels is: 5 ± 18 %, in third order channels 21 ± 32 %, in fourth order channels 73 ± 32 %, in fifth order channels 92 ± 23 %, and in sixth order channels is 100 %. In the Bassenthwaite, Coniston, Crummock, Duddon, Kent, Ullswater and Windermere catchments there is evidence of modification on all stream order channels (Fig. 6.15). In contrast, in the Calder, Caldew, Ennerdale, Esk, Haweswater, Sleddale, Sprint, Swindale and Wasdale catchments modification is concentrated on the higher order channels (third – fifth order channels), (Fig. 6.15).

There are statistically significant differences between the mean geomorphic characteristics of managed and natural river reaches in the study region (Table 6.5 and Fig. 6.5). For example, managed reaches have larger valley bottom widths, wider channels and lower channel slopes than natural reaches (Table 6.5). Managed channels have wider channel widths than natural channels because, firstly, management focuses on higher order channels which have larger channel widths than headwater (second or third order) streams; and secondly in some locations river management may involve over-widening the channel to increase capacity.

Table 6.5. Mean geomorphic characteristics of managed and natural SPs across the 17 catchments in the Lake District upland region (managed SP n = 373, natural SP n = 986).

	Managed		**Natural**	
	Mean	Std. Dev.	Mean	Std. Dev
Valley bottom width (m)	210	270	50	110
Channel width 2010 (m)	8	6	4.8	5
Specific stream power (W m^{-2})	220	245	550	430
Local slope (-)	0.03	0.05	0.10	0.09
Catchment area (km^2)	20	37	4	8

River management is focused on high order channels in the study region which are characterised as having large valley bottom widths (Figs. 6.7, 6.14). In natural systems, large valley bottom widths provide accommodation space for lateral planform adjustment (Schumm, 1977; Fryirs et al., 2016; O'Brien et al., 2019). However, lateral planform adjustments are restricted in high order channels in the study region due to modification (e.g. embankments, resectioning, flood defences) (Fig. 6.15) to protect valuable agricultural land and settlements. Therefore, in managed high order channels the spatial pattern and type of planform adjustment will vary from the natural expected downstream geometry laws. Understanding the location and presence of modifications to the river network is important for understanding the pattern of planform adjustments which will be discussed in Section 6.6.

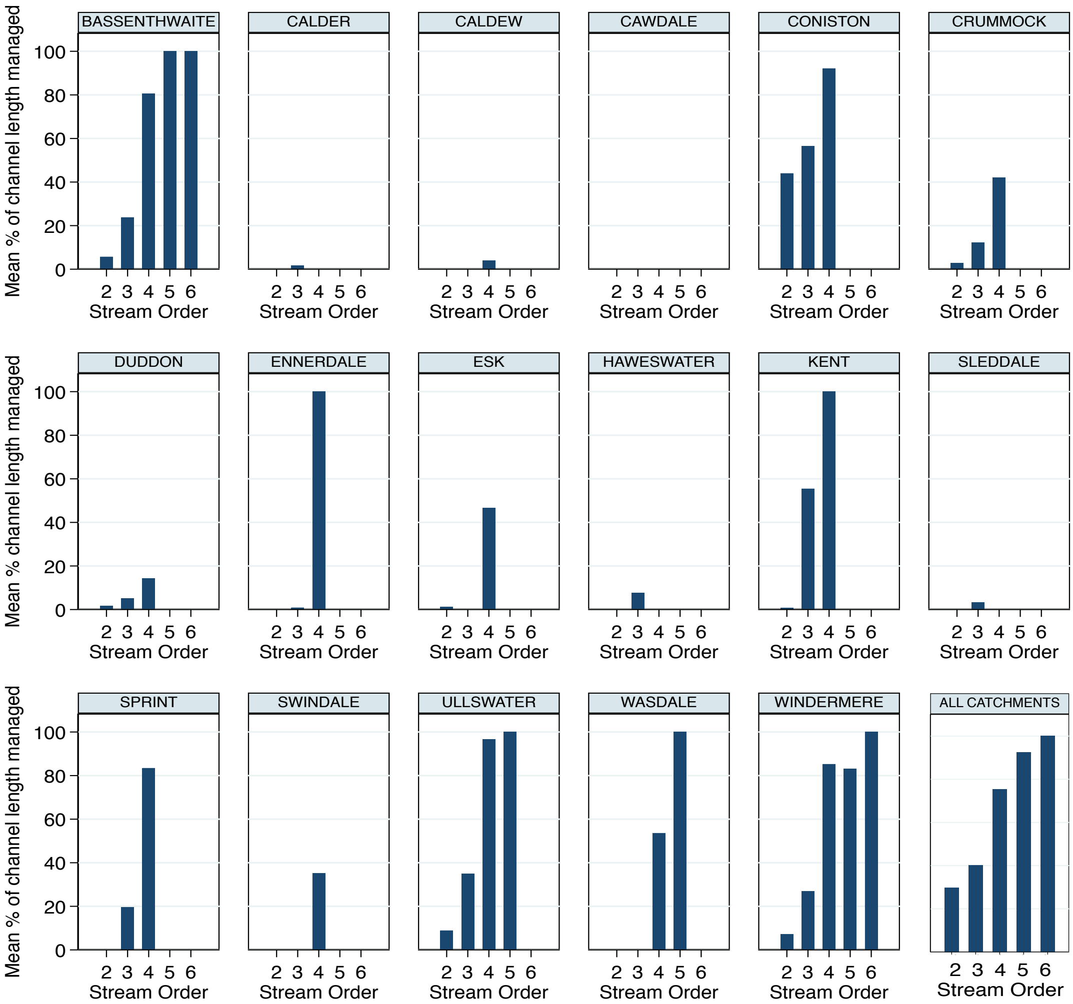


Figure 6.15 Mean percentage of channel length mapped as managed by stream order for each study catchment in the Lake District.

6.4.2.9 Summary of river and catchment geomorphic characteristics

Section 6.4.1 has presented the geomorphic characteristics of the rivers and catchments studied in the Lake District. The geomorphic characteristics: slope and specific stream power decrease, whereas, valley bottom width, channel width, catchment area increase through the stream order hierarchy, as expected according to stream order scaling laws (Leopold and Wolman, 1956; Gregory et al., 2004, (Table 6.3, Fig. 6.3). Catchment area (Fig. 6.6) showed the greatest number of statistical differences between the catchments due to variability in catchment shape (form ratio). Catchment form ratio is controlled by geological and glacial controls operating over the last millennium which have eroded a radial drainage pattern, and created U-shaped valleys with elongated or sphere shaped catchments. Therefore, catchment area is unlikely to be a suitable predictor of regional patterns of adjustment and stability. In contrast, no statistical differences were found between stream order and valley bottom width between the 17 catchments. Catchment to catchment comparisons have highlighted that there are differences between the geomorphic characteristics of the 17 catchments which influences the potential for adjustment. The following catchments were highlighted for their differences:

- *Haweswater (32.5 km^2)* has the mean steepest channels (0.14 ± 0.11), but narrow mean channel widths (4 ± 2 m), and mean valley bottom widths (70 ± 50 m). Mean specific stream power was highest in third order channels (530 ± 260 W m^{-2}) in the Haweswater catchment.
- *Wasdale (45 km^2)* has mean steep channel slopes (0.13 ± 0.11) and a high number of statistical differences between the other catchments. The catchment had the second largest area coverage of mass movements (14 %).
- *Calder (31 km^2)* has the mean narrowest valley bottom widths (60 ± 40 m) and lowest channel slopes (0.06 ± 0.03).
- *Ennerdale (44 km^2)* has steep mean channel slopes and the mean largest channel widths (10 ± 12 m). The catchment has an elongated shape and form ratio of 0.22. The catchment land cover is dominated by woodland. Mass movements occupy 17 % of the catchment area and if connected to the channel could provide an important sediment source to the channel. The catchment is dominated (47 %)

by the Ordovician felsic plutonic intrusion into the Skiddaw Group and the Borrowdale Volcanic Group.

- *Coniston (63 km^2)* has the mean widest second order channels (8 ± 11 m), this is 3 times the mean width of second order channels observed in the other 16 catchments due to anthropogenic modifications (presence of spoil heaps). Over 50 % of the channels are mapped as managed in the Coniston catchment.
- *Cawdale (8 km^2)* is the smallest catchment studied. It has the narrowest channel widths (3 ± 11 m) and narrow mean valley bottom (30 ± 50 m) and highest specific stream power values (900 ± 600 W m^{-2}), the catchment has one of the lowest percentages of channel length mapped as managed.
- *Bassenthwaite (362 km^2) and Windermere (240 km^2)* catchments represent the upper and lower zones of the upland sediment cascade with the lowest relief ratios These catchments have large valley bottom widths (Fig. 6.7) and the highest percentage of land cover categorised as suburban and over 40 % of the rivers show evidence of anthropogenic modification.

The above list highlights the catchments where there are significant differences in geomorphic variables and therefore it is expected that these catchments will have different patterns of erosion, sediment transfer and planform adjustment over the last *c.* 150 years in the upland region. For example, catchments with large valley bottom widths and channels connected to mass movements (e.g. Ennerdale) are hypothesised to have a high sediment supply, and accommodation space for lateral planform adjustment. Therefore, catchments with these characteristics are expected to display a higher frequency of adjustments, in particular boundary adjustments such as avulsions. In contrast, catchments with steep channel slopes, high specific stream powers and topographically confined channels (e.g. Haweswater) are expected to display a high degree of sediment continuity and relative 2D planform stability. The following section (Section 6.5) discusses the types of planform adjustments extracted in Part 2B of the methodology (Fig. 6.1) over the last *c.* 150 years. This is followed by Section 6.6, which links the patterns of planform adjustments to the geomorphic characteristics.

6.5 Patterns of adjustment and stability over the past *c.* 150 years

Part 2B of the methodology involves identifying channel planform adjustment types and stable reaches over the last *c.* 150 years (Fig. 6.1). In total, over all time epochs studied (intermediate periods: 1860s – 1950s, 1950s – 1980; 1980 – 1995; 1995 – 2004; 2004-2010; full period: 1860s – 2010) 29,832 stable and adjusting reaches were mapped. This section aims to describe the pattern of planform adjustments mapped. Section 6.5.1 firstly presents the results of the full period analysis (1860s – 2010) and discusses the differences in planform adjustment patterns between the 17 catchments studied. Section 6.5.2 explores the variability in planform stability over the intermediate periods across the study region.

6.5.1 Planform adjustment and stability over the full period (1860s – 2010)

The full period analysis compares channel planform from the 1860s historic map to the 2010 air photograph of the Lake District study region. The full period analysis therefore captures planform change over the last *c.* 150 years. Over this period, the total length of adjusting reaches mapped was 128 km (21 %) and stable reaches was 470 km (79 %).

Regionally, channel planform stability decreases through the stream order hierarchy over the full period, as expected with increasing channel width, sediment supply, catchment area and valley bottom width. The mean percentage of channel length mapped as stable is: 89 ± 16 % for second order channels, 75 ± 17 % for third order channels, 78 ± 17 % for fourth order channels, 74 ± 28 % for fifth order channels and 73 ± 26 % for sixth order channels. Therefore, there is a decrease in sediment continuity evidenced by an increase in planform adjustment activity downstream through the USC.

The mean length and frequency of planform adjustment and stability measured for the full period of analysis is summarised in Table 6.6. Bar adjustments are the most frequent forms of adjustment mapped, with the shortest mean length (Table 6.6). This result is to be expected given that the bar can be regarded as the fundamental geomorphic unit in fluvial systems (Nicholas et al., 1995; Church and Rice, 2009; Rice et al., 2009; Reid et al., 2020) and its morphodynamics indicate the state of sediment flux (continuity) within a particular river reach. Boundary adjustments are the longest adjustment and therefore affect the largest percentage of the river channel and include avulsions, cut offs and straightening (Table 6.6).

Table 6.6. Mean length (m) and frequency of adjustment and stable reaches for the full period (1860s – 2010) in the Lake District study region.

	Length (m)		Frequency
	Mean	*Std. Dev.*	*n*
Bar adjustment	25	31	3464
Bend adjustment	56	38	501
Boundary adjustment	132	131	240
Width adjustment	108	100	92
Stable	169	314	2776

Planform adjustment categories identified often occurred as combined processes (e.g. bar and bend adjustments). Over the full period of analysis, 903 planform adjustments (22 % of total number of adjustments mapped) occurred in combination with another form of adjustment. Of the total number of combined adjustments 53 % (n = 480) were bar and bend adjustments, 31 % were bar and boundary adjustments (n = 283), 12 % (n = 112) were bar and width adjustments, 3 % (n = 26) were bar, boundary and width adjustments, 2 % (n = 14) were boundary and with adjustments, and 2 % (n = 14) were different combinations of bar adjustments (i.e. bar accretion and bar reorganisation). This highlights that combined adjustment categories will have similar geomorphic characteristics and therefore may affect the identification of the controls discussed in Section 6.6. The following section discusses the between catchment patterns of adjustment and stability over the full period.

6.5.1.1 Full period (1860s – 2010) between catchment variability

There is between catchment variability in the percentage of rivers and streams mapped as adjusting or stable in the Lake District over the full period (Fig. 6.16). The Ennerdale and Wasdale catchments have the highest percentage of channel length mapped as adjusting (37 %, 8 km in Ennerdale and 32 %, 8 km in Wasdale), (Fig. 6.16B). In contrast, the Kent catchment has the lowest percentage of channel lengths mapped as adjusting (10 %, 1.2 km) over the full period (Fig. 6.16B).

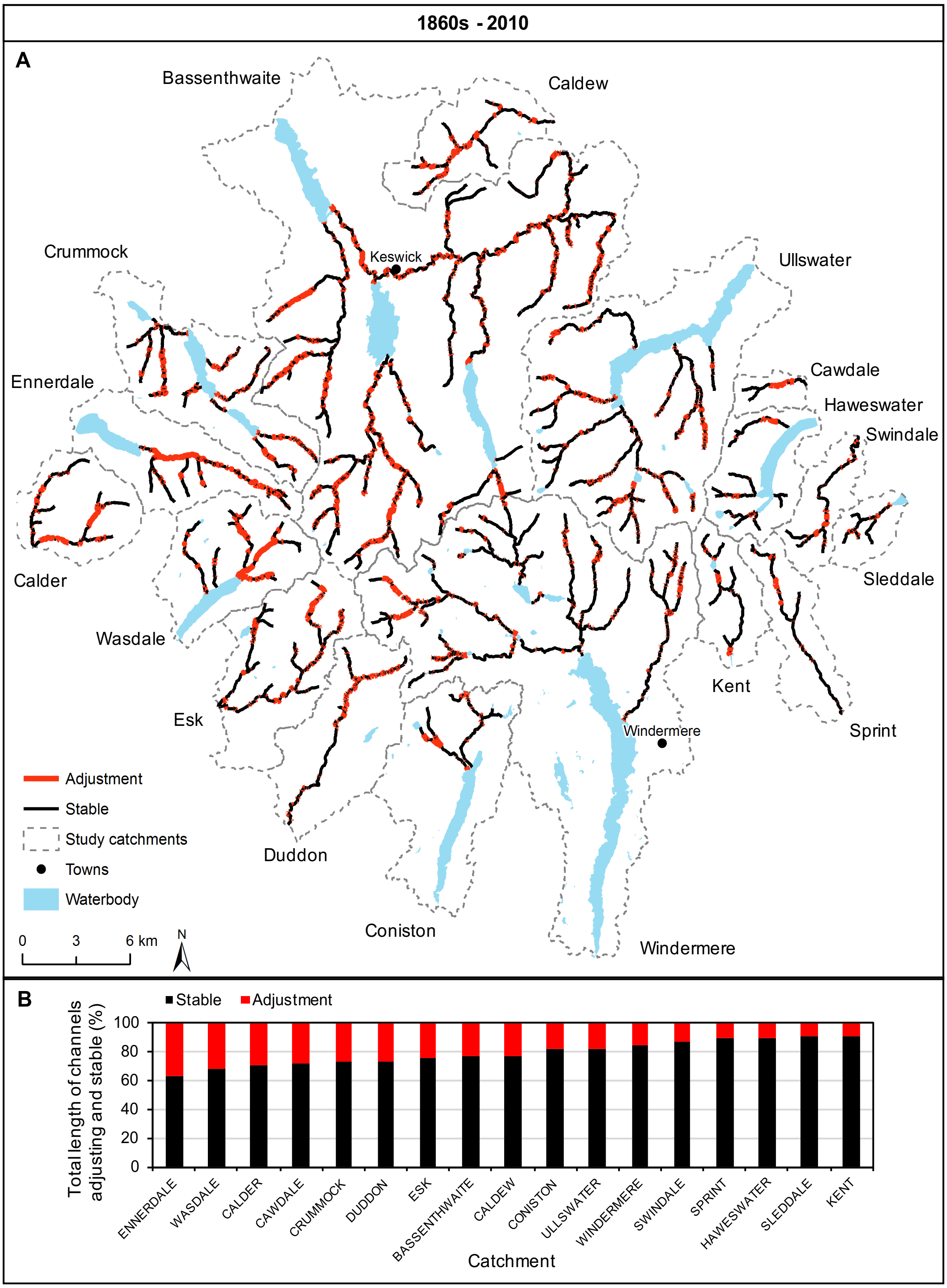


Figure 6.16. Planform adjustment and stable reaches 1860s – 2010 in the Lake District study region. (A) Spatial pattern of adjustment and stable reaches across the 17 study catchments. (B) Total percentage of channel length mapped as adjusting or stable by catchment.

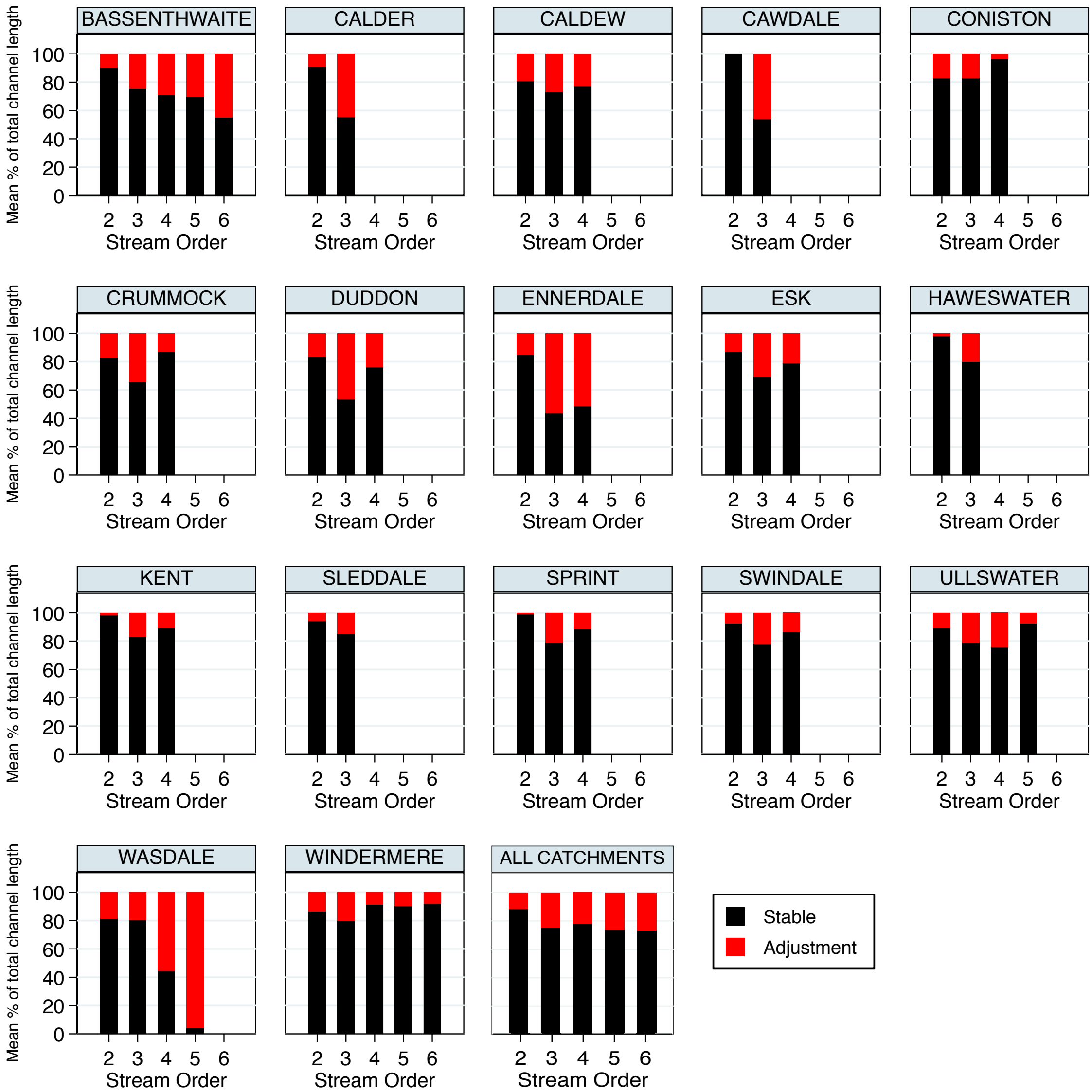


Figure 6.17. Mean percentage of total channel length mapped as stable or adjusting by stream order and catchment for 1860s – 2010 period.

In the Bassenthwaite, Wasdale, Calder and Ennerdale catchments there is a downstream increase in the mean percentage of channel mapped as adjusting by stream order (Fig. 6.17). However, in the Crummock, Caldew, Coniston, Duddon, Esk, Kent, Sprint, Swindale, Ullswater and Windermere catchments there is a decrease in the mean percentage of channel length mapped as adjusting in the highest stream order channel (Fig. 6.17). A decrease in adjustment length downstream indicates a local increase in channel stability, this could be due to an increase in channel management restricting lateral adjustment in high order channels in these catchments (Fig 6.14).

Figure 6.18 displays the frequency and length of planform adjustments per catchment. The Bassenthwaite, Windermere, and Ullswater catchments have the highest frequency of planform adjustment for the full period (Fig. 6.18), these catchments have the highest total number of rivers studied and largest catchment areas (Table 6.2). Cawdale has the lowest number of adjustments and stable reaches mapped (n = 24), this is the smallest catchment studied with the narrowest channel widths. Bend adjustments in the Cawdale catchment had the highest frequency for the full period (n = 12), (Fig. 6.18). Bar adjustments, boundary and bend adjustments were observed across all catchments (Fig. 6.18). No major singular width adjustments (e.g. >50 % change in channel width) were observed in the Cawdale or Swindale catchments over the full period (Fig. 6.18).

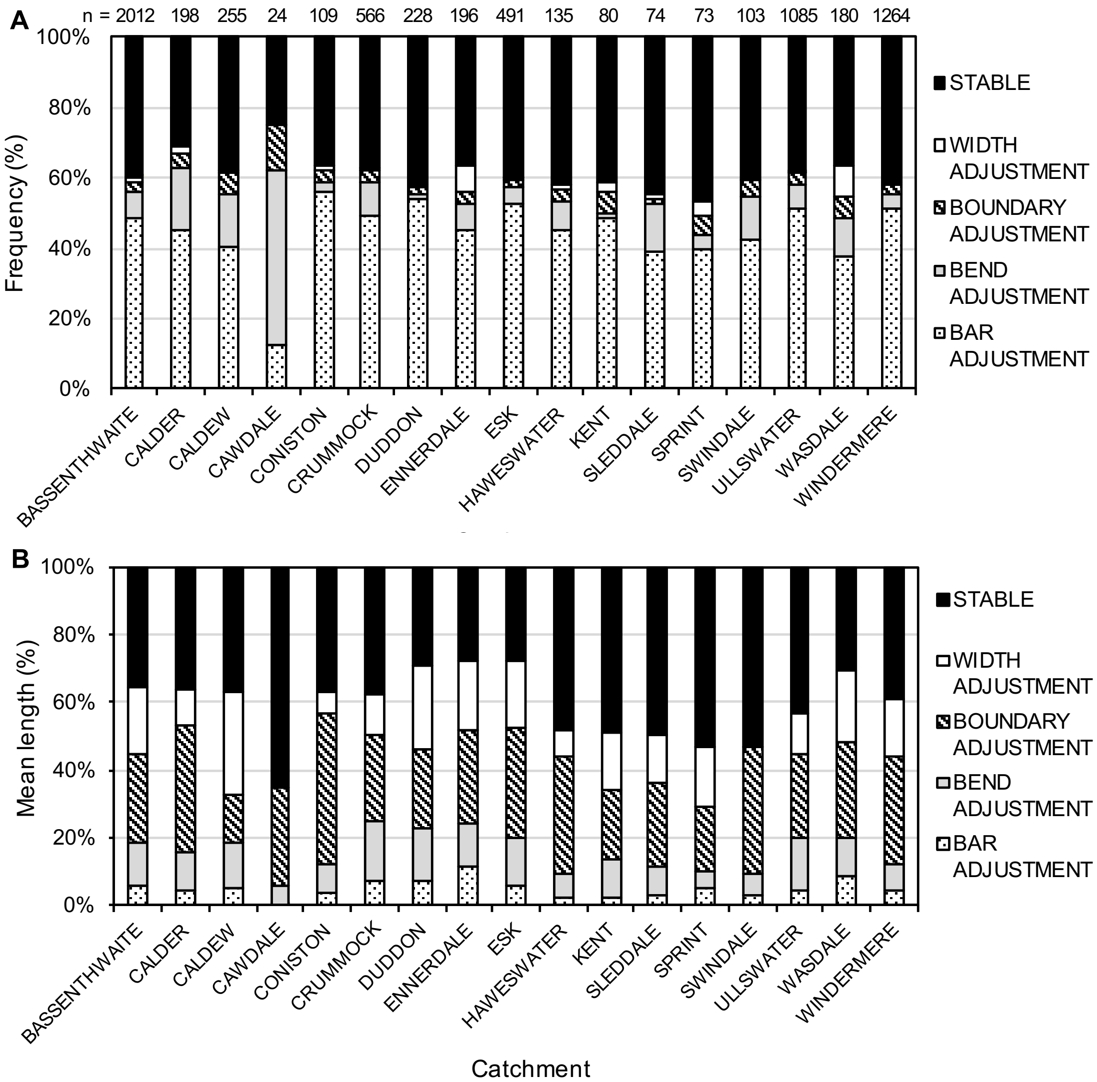


Figure 6.18. Frequency (A) and mean length (B) of adjustment and stable reaches for 1860s – 2010 period by catchment in the Lake District study region.

Stable reaches made up the greatest proportion of channel length in all catchments, followed by boundary adjustments (Fig. 6.18B). The mean length of boundary adjustments was highest in the in the Coniston catchment (363 ± 170 m), in contrast in the Caldew catchment boundary adjustments have the shortest mean length (61 ± 41 m), (Fig. 6.18B). Width adjustments had the mean longest length in the Wasdale catchment (175 ± 172 m) and shortest lengths in the Ullswater (39 ± 10 m) and Crummock (38 ± 14 m) catchments. Bar adjustments had the longest length in the Ennerdale (83 ± 81 m catchment, and lowest in the Cawdale catchment (5 ± 3 m), which also had the lowest frequency of bar adjustments (n = 3), (Fig. 6.18B).

Figure 6.19 and 6.20 summarise the frequency and mean length of planform adjustments by stream order and catchment for the 1860s – 2010 period. In Cawdale, second order channels are mapped as stable. In second order channels in the Kent catchment bar adjustments are the only adjustment mapped, with a mean length of 11 ± 4 m. No bend adjustments are mapped in third order channels in the Kent catchment. In the Sleddale catchment, bar and bend adjustment are most frequent in second order channels, however, these have a small mean length and stable reaches dominate. Third order channels in the Ennerdale catchment have the highest number of major width adjustments mapped (n = 9). Downstream, in fourth, fifth and sixth order channels boundary adjustment frequency and mean length of adjustments decrease, this could be due to the presence of lakes truncating channel length or anthropogenic modifications in lower floodplain valley setting restricting adjustment. In the Ullswater, Coniston, and Esk catchments no boundary adjustments were observed in fourth order channels over the full period (Figs. 6.19, 6.20). Therefore, there is between catchment variability in the length and type of planform adjustment identified over the full period (Figs 6.19, 6.20).

The full period analysis provides an overview of planform adjustment across the upland region over the last *c.* 150 years. The Ennerdale and Wasdale catchments were highlighted as active catchments, showing the highest percentage of adjustment (Fig. 6.16). In contrast, the Sleddale and Kent catchments showed relative stability, particularly in second order channels where the majority of the channels are mapped as stable (Fig. 6.17). This data will be compared to river and catchment geomorphic characteristics in Section 6.7 to identify the controls on adjustment and stability.

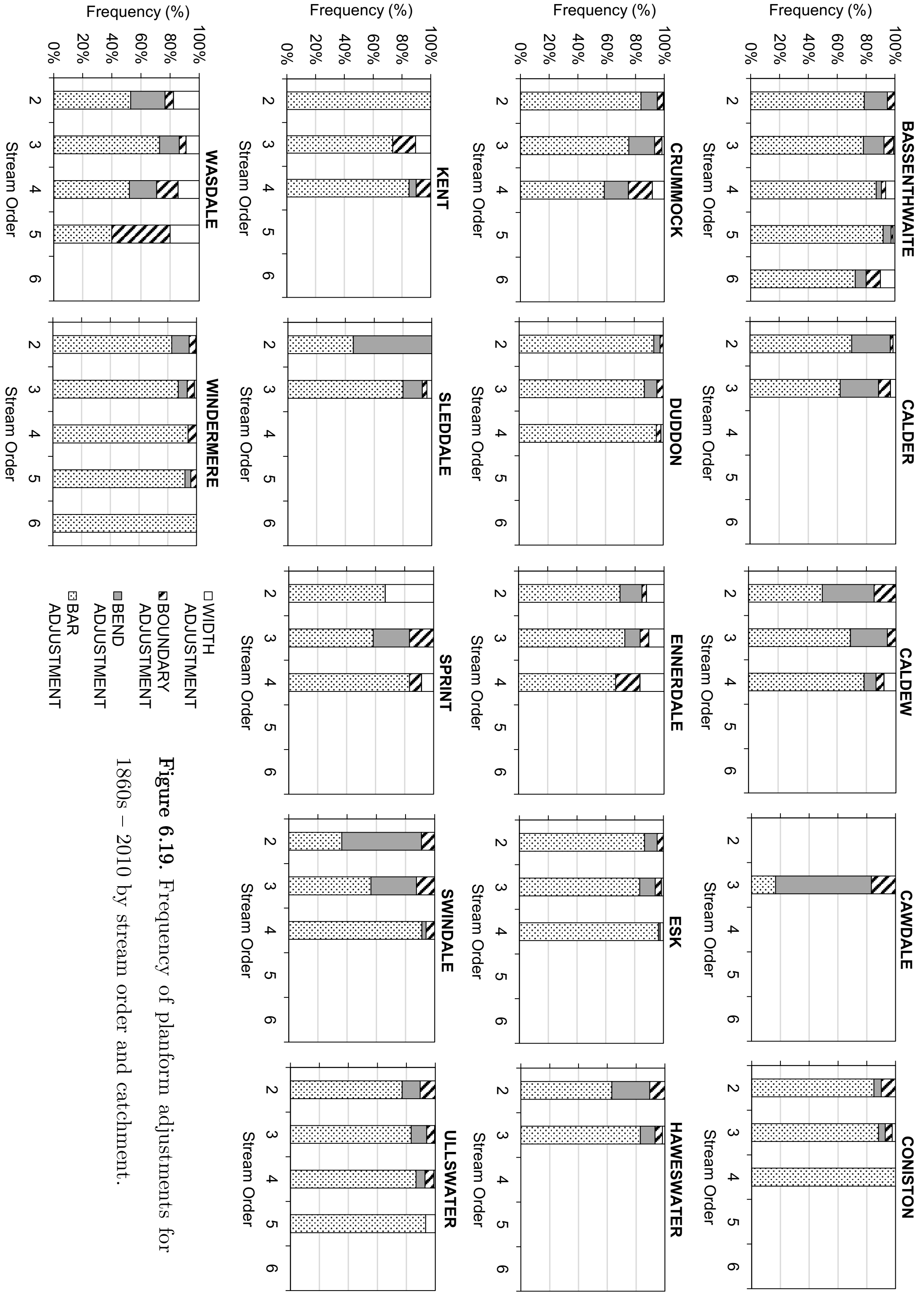


Figure 6.19. Frequency of planform adjustments for 1860s – 2010 by stream order and catchment.

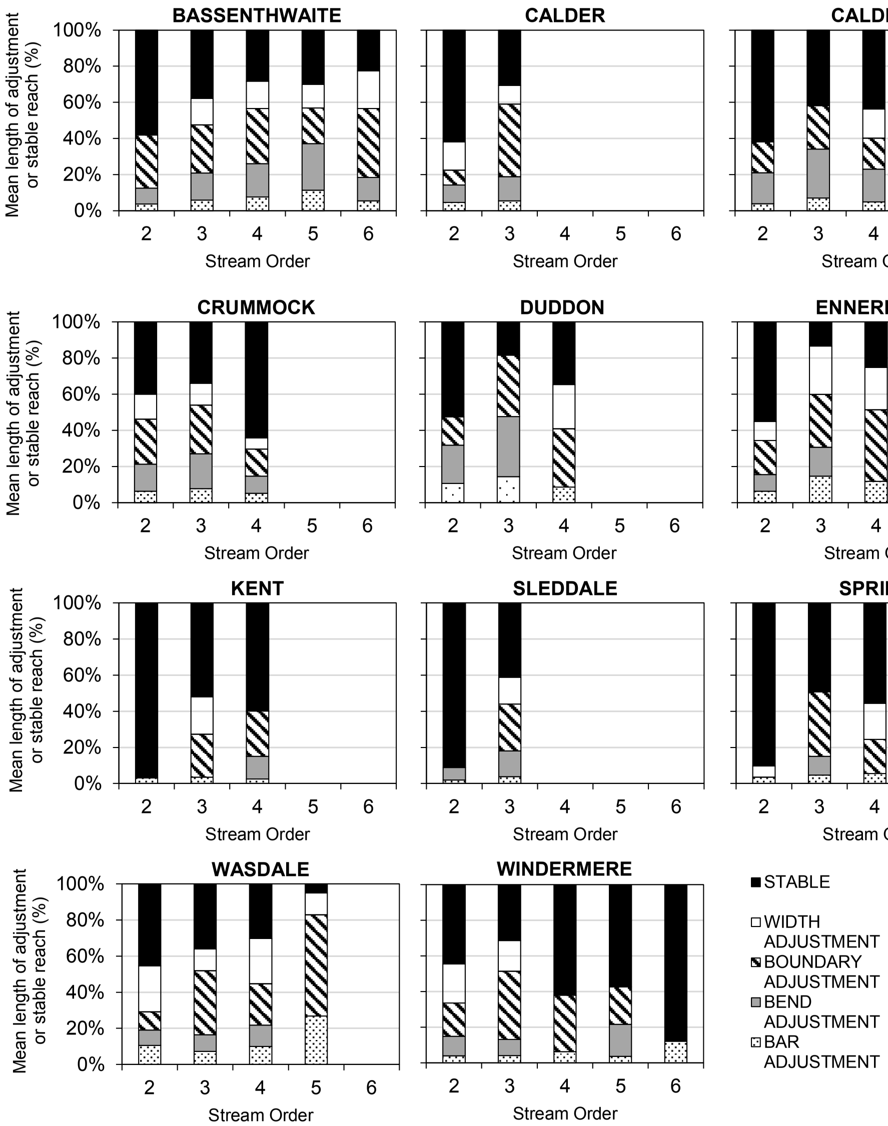


Figure 6.20. Mean length (%) of channel affected by stable or adjustment for 1860s – 2010 by stream order and catchment.

6.5.2 Intermediate periods planform adjustment and stability

The spatial pattern of planform adjustment for the region across the intermediate and full periods of analysis is shown in Figure 6.21. The 1860s-2010 full period data is included in Figure 6.21 for comparison. The full period analysis shows a similar pattern of percentage adjustment to the intermediate periods and therefore indicates that the full period provides a representative overview of planform adjustment and stability over the period of measured change.

In the study region, catchments showing persistent adjustment and/or stability can be readily identified from the temporal analysis. For example, the Ennerdale catchment shows the highest percentage of channels mapped as adjusting in the 1950s-1980, 1995–2004 and 1860s–2010 period (Fig. 6.22). In the 1860s – 1950s, and 1980–1995 and 2004-2010 the Ennerdale catchment has the second highest percentage of channels mapped as adjusting (Fig. 6.22). Similarly, the Wasdale (mean adjustment length = 23 %) and Calder (mean adjustment length = 22 %) catchments have a high percentage of channels mapped as adjusting over all time periods (Fig. 6.22).

In contrast, there are some catchments, which show particular epochs with increases in the percentage of adjustments, which could be due to local catchment scale variability in flood events or anthropogenic activity (Fig. 6.22). For example, in the Duddon catchment, over the 1980 – 1995 period, the highest percentage of channel length mapped as adjusting (33 %) is recorded (Fig. 6.22). In the previous two epochs studied (1860s – 1950s, and 1950s – 1980) the Duddon catchment was relatively stable with less than 6 % of channels mapped as adjusting. The increase in the percentage of channels mapped as adjusting in the Duddon catchment is observed in third order channels, this jump could be attributed to the changing resolution of data sources used (comparison between historic map and air photograph) or related to local catchment forcing (e.g. flood event, anthropogenic activity). After the 1980-1995 period the Duddon catchment lies amongst the top 5 catchments with the highest percentage of channels mapped as adjusting in the 1995 – 2004 and 2004-2010 periods, suggesting there has been a local change in exogenic or endogenic forcing influencing sediment continuity following the 1860s-1950s period.

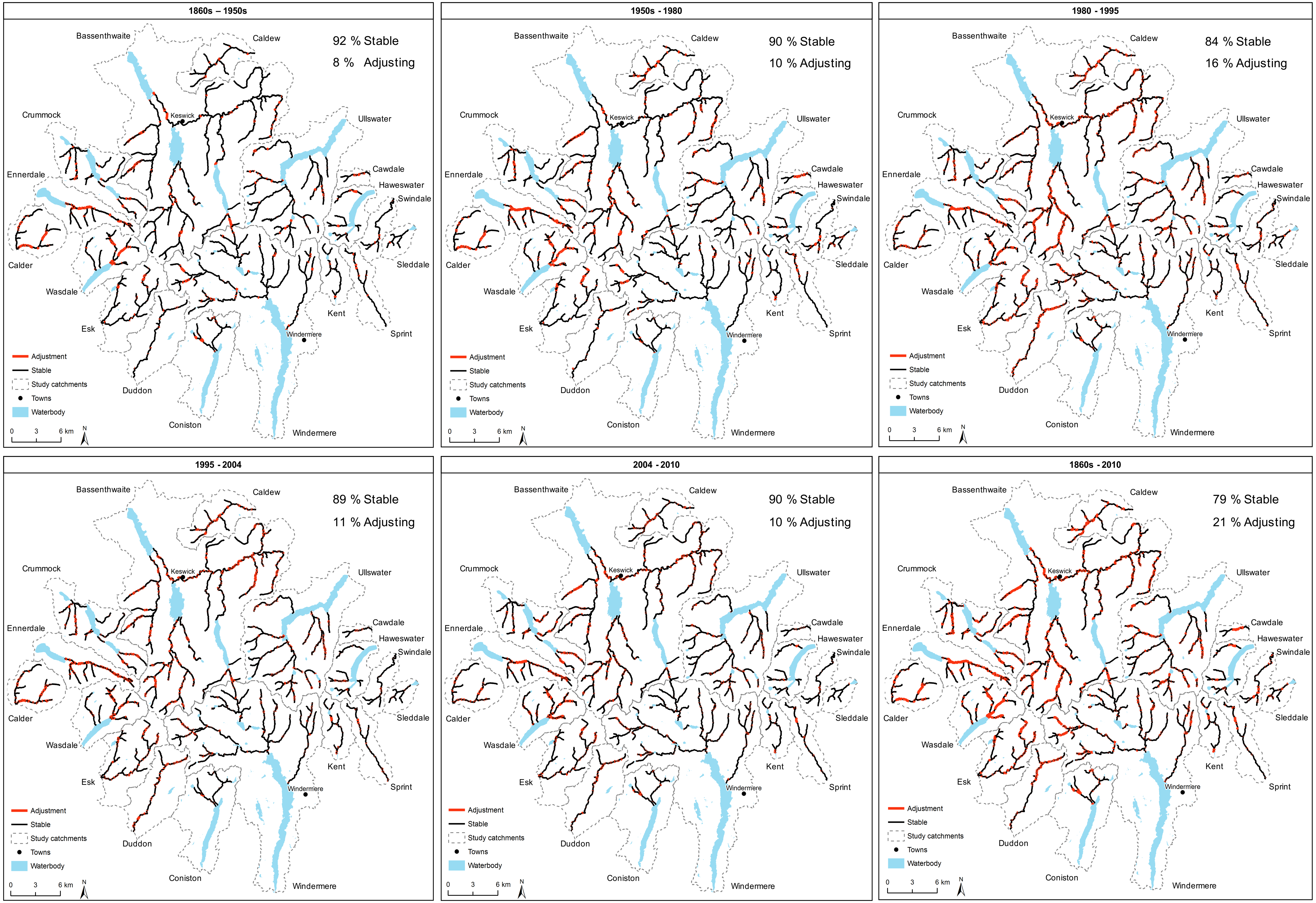


Figure 6.21. Spatial patterns of planform adjustment and stability over all time periods studied in the Lake District upland study region. Percentages indicate the total length of channels mapped as 2D stable or adjusting.

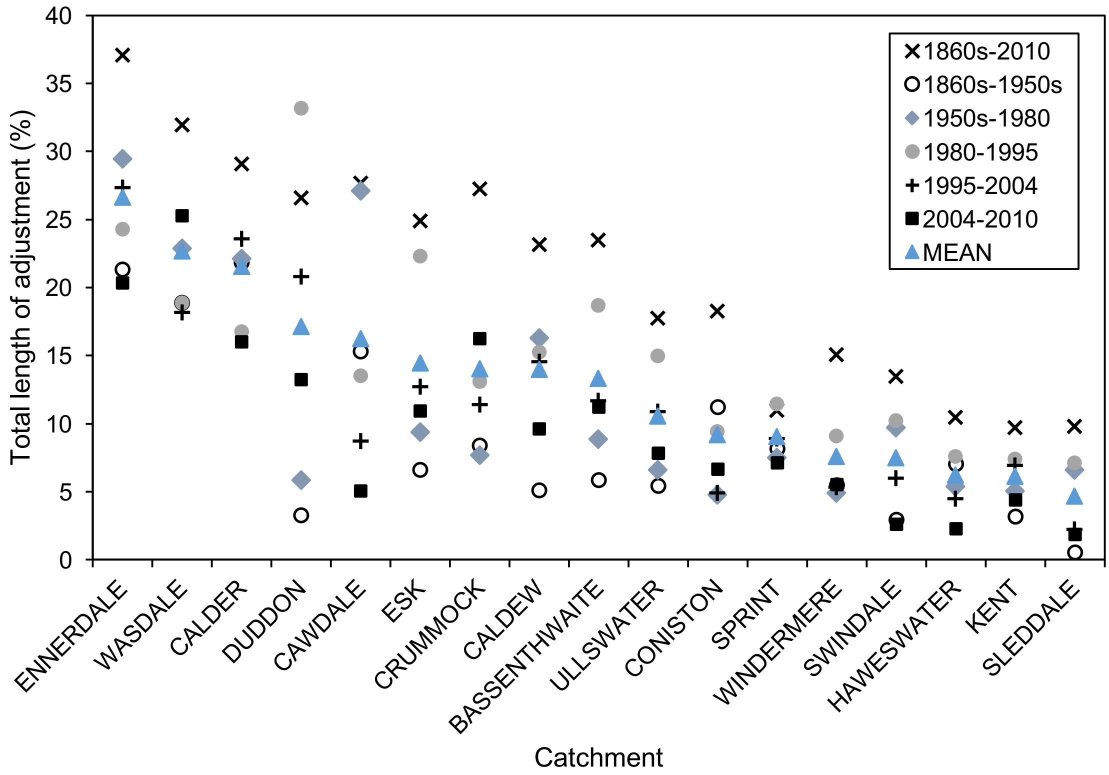


Figure 6.22. Total length of channels adjusting by catchment over all time periods in the Lake District Study region. Blue triangles indicate the mean percentage of channels mapped as adjusting by catchment. Data is ranked by mean adjustment percentage over all time periods.

The Sleddale (mean length adjusting = 5 %), Kent (mean length adjusting = 6 %) and Haweswater (mean length adjusting = 6 %) catchments have the lowest percentage of channels mapped as adjusting and show consistent 2D planform stability over all time periods (Fig. 6.22). The Coniston catchment had the lowest percentage of channel mapped as adjusting (5 %) during 1950s – 1980 (Fig. 6.22). However, in the preceding epoch (1860s – 1950s) the percentage of channel mapped as adjusting in Coniston was double (11 %) the 1950 – 1980 percentage. Planform adjustment during 1860s – 1950s is concentrated in second order channels and could be a result of anthropogenic activity and Copper works peak production during the 1850s – 1870 period. The low level of activity in 1950 – 1980 period could indicate the system has recovered in response to anthropogenic activity and has reached a new equilibrium, or the channel has been artificially modified to reduce channel activity.

6.5.2.1 Artificial planform adjustments

It is important to recognise that planform adjustments mapped over the last *c.* 150 years might not all be 'natural' and can be a result of direct anthropogenic activity (Brookes, 1988). For example, channels have been historically straightened and widened to increase channel capacity (Brookes, 1988) and may be mapped as lateral expansion or avulsions. Direct anthropogenic planform adjustment is difficult to identify in historical sources (and often pre-dates the earliest historical maps), but can often be identified where there is an abrupt change in channel planform, for example, where a channel had a historical sinuous course and now has a straight planform. Anthropogenic adjustments most commonly occur in high order channels in populated areas to protect settlements from flooding. When planform adjustments were mapped (Part 2B, Fig. 6.1) it was noted if an adjustment appeared to be artificial. This is likely to be an underestimate of anthropogenic adjustments, but provides additional context for interpreting the patterns of adjustment and stability observed across the study region.

Over all time periods studied 144 adjustments were recorded as artificial, affecting a mean 7 ± 10 % of the river channel length. Artificial adjustments included major changes in channel planform such as avulsion (or re-routing), (n = 97), width adjustment (n = 32) and bend adjustments (n = 15). The highest frequency of artificial adjustments was observed in lowland catchments that have a higher percentage of managed rivers (Fig. 6.14). For example, the number of artificial adjustments in Bassenthwaite was 58, in Windermere was 31, and in Ullswater was 12. It is important to recognise that a proportion of the planform adjustments mapped may be artificial and this will influence the correlations between planform adjustment type and geomorphic characteristics discussed in Section 6.6.

6.5.3 Summary of temporal pattern of adjustment and stability

This section has presented the temporal patterns of planform adjustment and stability across the 17 catchments in the Lake District study region extracted from Part 2B of the methodology (Fig. 6.1). Over the full period of analysis (1860s-2010) 21 % of channels studied were mapped as adjusting. Spatially, catchments of persistent adjustment identified in the upland region include: Ennerdale, Wasdale and Calder. Catchments of persistent stability include: Haweswater, Sleddale, and Kent. Over the intermediate periods there is catchment variability in the percentage of adjustment and stability (Figs. 6.21, 6.22) For example, in the Coniston catchment the highest percentage of channel length mapped as adjusting was observed over the 1860s – 1950s period. In contrast, in the Duddon catchment there was a spike in the percentage of channel mapped as adjusting over the 1980 – 1995 period, indicating temporal variability in patterns of adjustment. The temporal analysis presents a 'snapshot' of river planform adjustment over the period of the last *c.* 150 years and is useful for exploring the dominant patterns of channel stability using the best available historical data. The following section (Section 6.6) aims to identify the geomorphic characteristics influencing the different patterns of planform adjustment types mapped spatially over the period of measured change.

6.6 Geomorphic characteristics of adjustment and stable reaches

The objective of this section is to use the data collected and discussed in Section 6.4 and 6.5 to consider the geomorphic variables influencing the location and extent of planform adjustment and stability. It is hypothesised that adjusting reaches will have differing characteristics (e.g. channel width, valley bottom width, specific stream power and slope) to stable reaches.

6.6.1 Regional patterns: slope, valley bottom width, channel width, stream power and catchment area influence on planform adjustment and stability

A one-way ANOVA identified a statistically significant difference (p value <0.05) between geomorphic characteristics: valley bottom width, channel width, slope and specific stream power between stable and adjusting reaches (Table 6.7). Figure 6.23 displays the variability in geomorphic characteristics for adjustment and stable reaches for the full dataset.

Channel width and valley bottom width is larger in adjusting reaches, and channel slope and specific stream power is lower in adjusting reaches compared to stable reaches (Table 6.7). This is expected, as larger valley bottom and channel widths provide accommodation space available for lateral planform adjustment and lower specific stream powers can lead to sediment deposition and the formation of in-channel bars (Knighton, 1999; Reinfelds et al., 2004; Lea and Legleiter, 2016). There were no statically significant differences between stable and adjusting reaches for catchment area across the regional dataset (Table 6.7). Therefore, reaches of adjustment and stability can be characterised by the variables: valley bottom with, channel width, specific stream power and slope.

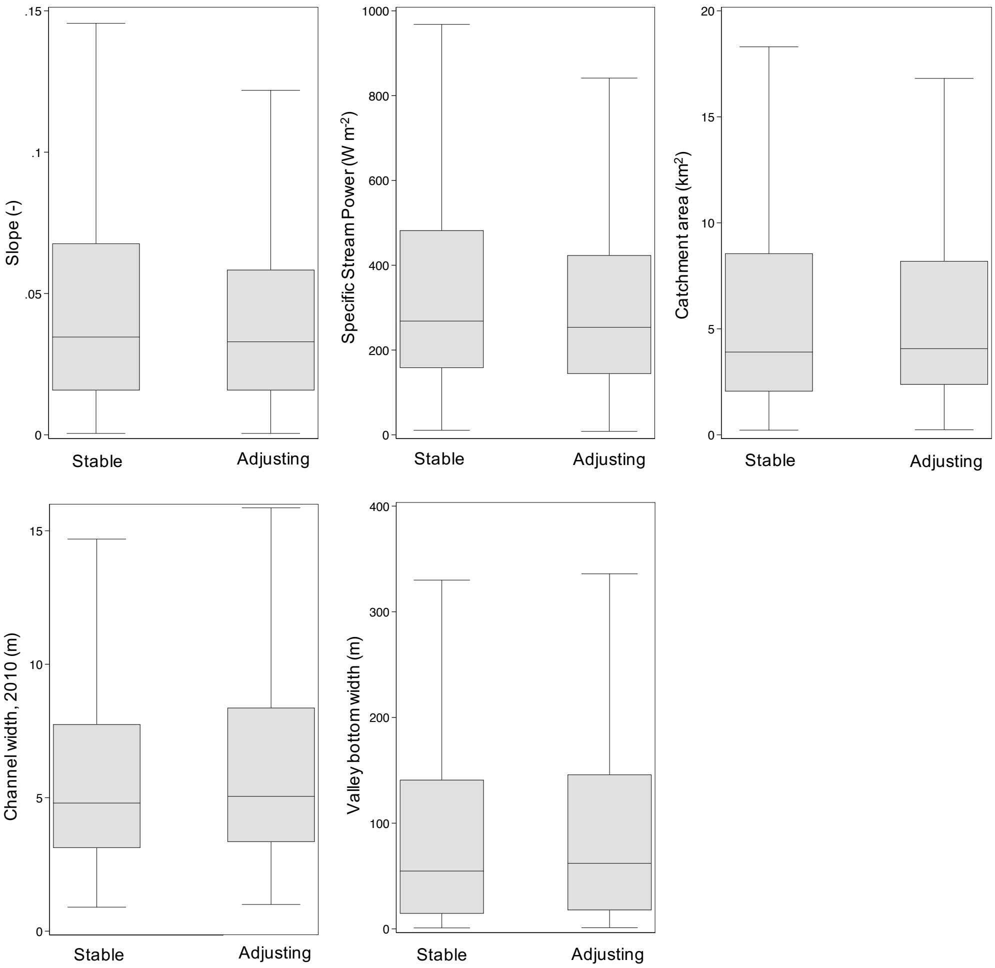


Figure 6.23. Geomorphic characteristics of stable (n = 13377) and adjusting (n = 16455) reaches for all catchments and time periods in the Lake District (plots exclude outside values).

Table 6.7. One-way ANOVA showing statistically significant differences between stable (n = 13377) and adjusting (n = 16455) reaches for the geomorphic characteristics. Grey shaded cells indicate presence of statistically significant differences (95% confidence interval) between adjusting and stable reach characteristics.

Variable	Stable / Adjusting	Mean	Std. Dev.	*p* value
Valley Bottom Width (m)	Stable	111.6	172.7	0.000
	Adjusting	120.8	189.4	
Channel Width (m)	Stable	6	5	0.000
	Adjusting	7	6	
Catchment Area (km^2)	Stable	11.3	26.3	0.388
	Adjusting	11.5	28.4	
Specific Stream Power ($W\ m^{-2}$)	Stable	344.9	260.3	0.000
	Adjusting	311.4	240.3	
Channel slope (-)	Stable	0.052	0.053	0.000
	Adjusting	0.046	0.045	

Tukey (HSD) analysis was performed after the one-way ANOVA to identify if a statistically significant difference between the mean geomorphic variables and the adjustment categories and stable reaches was present. This information is useful to identify the variables that can explain and predict adjustment occurrence. Table 6.8 summarises the total number of statistically significant differences between the adjustment categories and geomorphic characteristics. The geomorphic variables channel width (n* = 59) and valley bottom width (n* = 47) had the highest number of statistically significant differences between adjustment types and the geomorphic variables across the region. Of the adjustments, statistical differences in valley bottom width and channel width were highest between bend adjustments and boundary adjustments, and width adjustment and stable reaches (Table 6.8). For example, mean valley bottom width of bend adjustments was 96 ± 130 m, for stable reaches was 112 ± 170 m. Therefore, valley bottom width and channel width represent the best variables for predicting large scale adjustments such as boundary and width adjustments.

Table 6.8. Total number of statistically significant differences (p-value <0.05) from Tukey (HSD) analysis between the adjustment categories and geomorphic characteristics for all catchments and stream orders. A is local catchment area (km^2), W is channel width (2010 m), VW is valley bottom width (m) and ω is the specific stream power (W m^{-2}). Highlighted column indicates the geomorphic variables with the highest number of statistically significant differences and are therefore the best predictor of planform adjustment categories.

	Geomorphic variables					
Comparison between adjustment categories	*S*	*A**	*W*	*VW*	*ω*	*Total*
Bar Adjustment vs Bend Adjustment	4		7	5	3	*27*
Bar Adjustment vs Boundary Adjustment	4		2	3	2	*15*
Bar Adjustment vs Width Adjustment	1		9	5	2	*22*
Bar Adjustment vs Stable	9		8	6	11	*37*
Bend Adjustment vs Width Adjustment	0		2	3	0	*6*
Bend Adjustment vs Boundary Adjustment	3		9	6	3	*27*
Bend Adjustment vs Stable	4		5	6	3	*24*
Boundary Adjustment vs Width Adjustment	3		6	3	2	*18*
Boundary Adjustment vs Stable	1		2	4	2	*11*
Width Adjustment vs Stable	3		9	6	5	*29*
Total	*32*		*59*	*47*	*33*	

**Catchment area excluded from analysis as no statistically significant differences were identified after one-way ANOVA (c.f. Table 6.7).*

In the study region, stable reaches have steeper mean channel slopes and higher specific stream power values than adjusting reaches (Fig. 6.23, Table 6.7). High specific stream power values and steep channel slopes indicate high energy systems and therefore sediment erosion and transfer are likely to be dominant. Figure 6.24 displays the relationships between stream power and channel slope for the adjustment and stable categories. Previous studies have stated that planform adjustment will occur via erosion when specific stream power values exceed 35 W m^{-2} (Brookes, 1987) and floodplain erosion will occur over 300 W m^{-2} (Baker and Costa, 1987; Magilligan, 1992; Fuller, 2008). The results documented here indicate that planform adjustments occur above and below these thresholds (Fig. 6.24). For example, bar adjustments occur on specific stream powers between 8 – 1800 W m^{-2}, bend adjustments between 15 - 1600 W m^{-2}, width adjustments 8 – 1600 W m^{-2}, boundary adjustment 8 – 1120 W m^{-2}, and stable reaches 11 – 1600 W m^{-2}. This pattern is observed because there are multiple geomorphic variables influencing planform adjustment. For example, in the Lake District study high specific stream power and slope values were observed in second order headwater channels which were topographically confined (Fig. 6.8) therefore limiting the space available for lateral planform adjustment. The dominant forms of adjustment in low order channels were bar adjustments (Fig. 6.19). Low order channels with high specific stream power values categorised as stable are likely to be adjusting vertically, and any material eroded is likely to be transported due to the high stream power thresholds identified (Fig. 6.24).

As valley bottom width increases downstream it is hypothesised that channel width will increase, and therefore the potential for planform adjustment will increase as there is more space for lateral adjustment (Schumm, 1977; Church, 1996; Fryirs et al., 2016; O'Brien et al., 2019). Mean valley bottom width and channel width is larger for adjusting reaches than stable reaches (Table 6.7). However, regionally, there is a weak relationship between channel width and valley bottom width for adjusting and stable categories (Fig. 6.25). Lake District rivers have a legacy of modification, by straightening, re-sectioning and reinforcement, these modifications alter channel width (narrow or widen) therefore affecting the relationships observed in Figure 6.25. The influence of modification on planform adjustment patterns will be investigated further in Section 6.6.3.

This analysis highlights that variations in valley bottom width, channel width, slope and specific stream power are important variables for explaining planform adjustment and stability (Table 6.7). The following section will explore if these patterns are consistent between the 17 catchments in the Lake District study region.

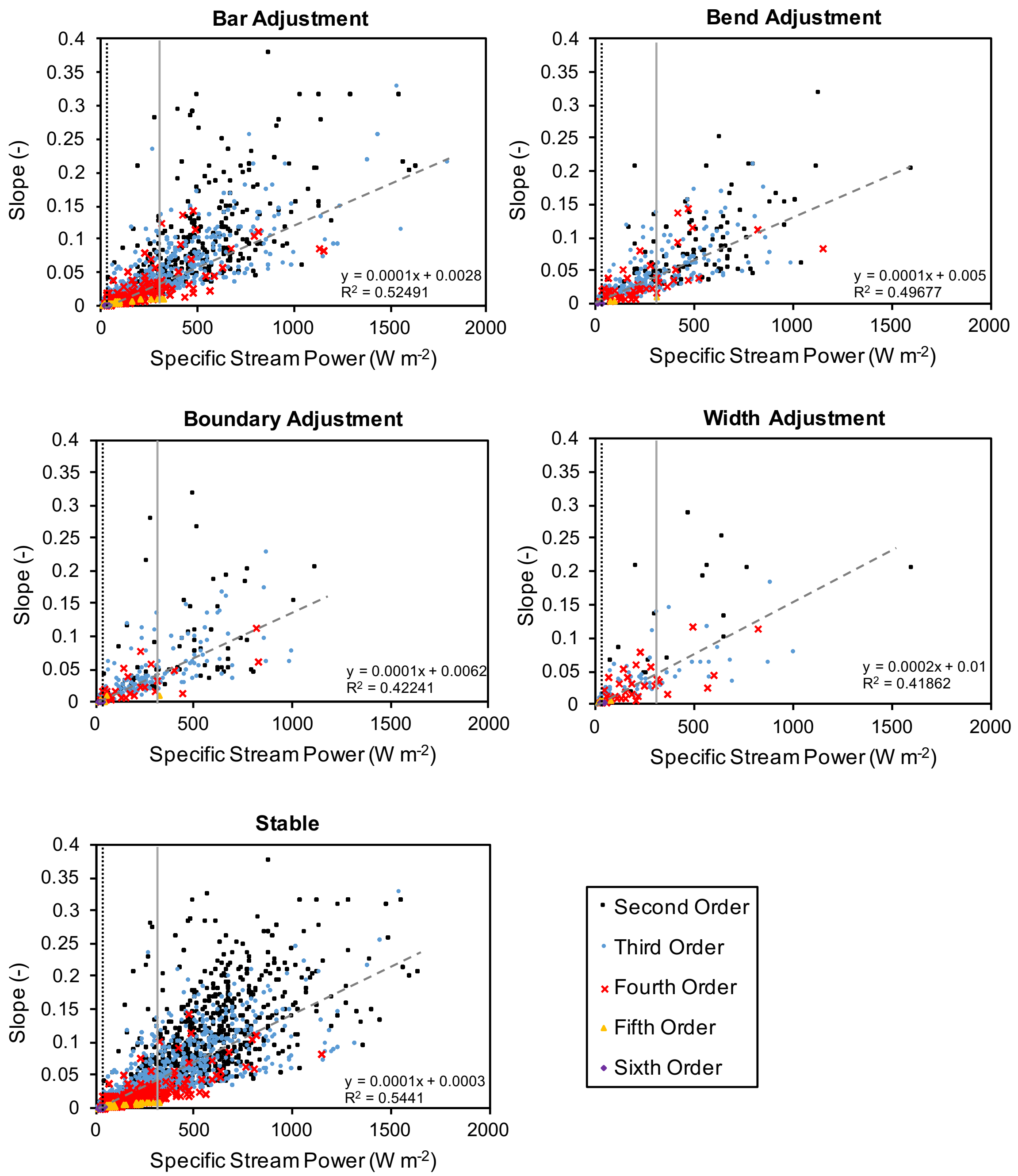


Figure 6.24. Geomorphic characteristics: slope and specific stream power plotted for the adjustment and stable categories for the Lake District study region. Points are colour coded by stream order. Dashed black line indicates 35 W m^{-2} (Brookes, 1987) specific stream power threshold where erosion will occur. Continuous grey line is 300 W m^{-2} (Baker and Costa, 1987; Magilligan, 1992; Fuller, 2008) specific stream power threshold where floodplain erosion is reported to occur.

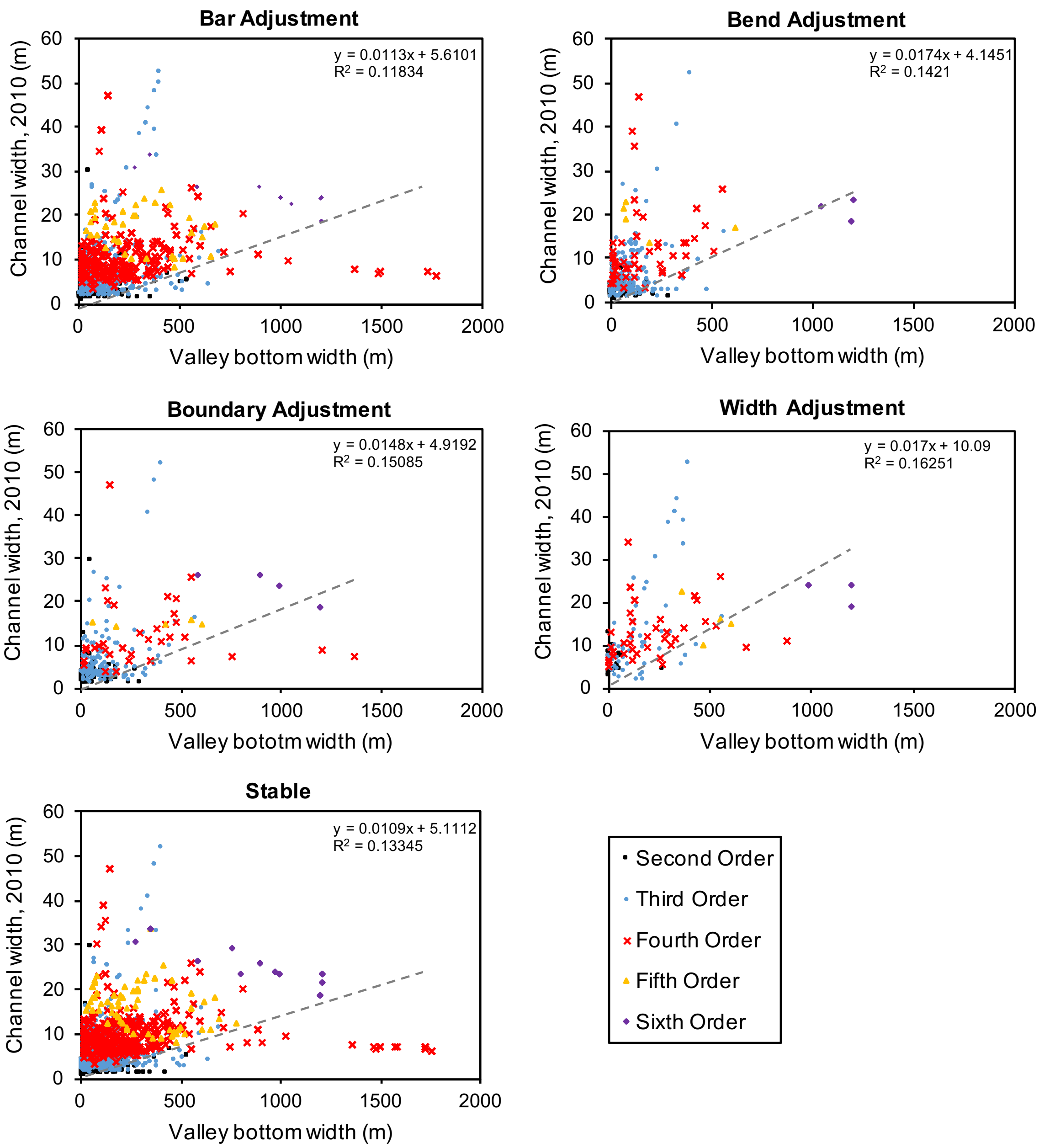


Figure 6.25. Geomorphic characteristics: valley bottom width and channel width plotted for the adjustment and stable categories colour coded by stream order for the Lake District study region.

6.6.2 Between catchment variability: slope, valley bottom width, channel width, stream power influence on planform adjustment and stability

Figure 6.26 summarises the mean geomorphic characteristics of adjusting and stable reaches by catchment. The Wasdale and Ennerdale catchments were identified as some of the most actively adjusting catchments (Section 6.5) over all time periods and show the largest differences in geomorphic characteristics (valley bottom width, local slope, channel width) between stable and adjusting reaches compared to the other catchments (Fig. 6.26). For example, the channel width of adjusting reaches in the Ennerdale catchment is 17 ± 13 m and in the Wasdale catchment is 11 ± 6 m. The lowest mean channel widths of adjusting reaches were observed in the Cawdale (3 ± 1 m) and Haweswater catchment (4 ± 1 m). This demonstrates that the dimensions of adjusting reaches vary on a catchment by catchment basis.

In contrast, the Kent and Sleddale catchments showed persistent stability over all time periods and the mean geomorphic characteristics of stable and adjusting reaches lie around the mean of the whole dataset (Fig. 6.26). The Haweswater catchment also showed persistent stability over the last *c.* 150 years, however, has the highest specific stream powers and steepest local slopes of stable and adjusting reaches (Fig. 6.26). Haweswater was one of the stand-out catchments, with different geomorphic characteristics to the other catchments, identified in Section 6.4. Channels in Haweswater are topographically confined with narrow channel widths and therefore major lateral 2D planform adjustments were not observed, despite the high specific stream powers (Fig. 6.26). Channels in the Haweswater catchment may be adjusting vertically over the time period studied.

One-way ANOVA and Tukey (HSD) analysis was performed to explore the statistical differences between adjustment categories, geomorphic characteristics, stream order and catchment; data tables documenting the number of statistical differences are collated in Appendix C. The highest number of statistically significant differences between the geomorphic characteristics and adjustments in the catchments were observed in third order channels ($n^* = 97$). Third order channels had the highest frequency of planform adjustments observed over all epochs ($n = 16177$). The highest number of statistically significant differences between adjustment categories and geomorphic variables were in the Bassenthwaite ($n^* = 33$), Ennerdale ($n^* = 31$) and Wasdale ($n^* = 27$) catchments. The Ennerdale, Wasdale and Bassenthwaite catchments displayed the highest number of statistical differences in the geomorphic characteristics (e.g. slope, valley bottom width, channel width) identified in Section 6.4 so this result is expected. In contrast, in the Cawdale and Caldew catchments no significant differences were identified between the geomorphic characteristics and adjustment categories. Valley bottom width and channel width were therefore the best predictors of planform adjustment and stability at the regional and catchment scale.

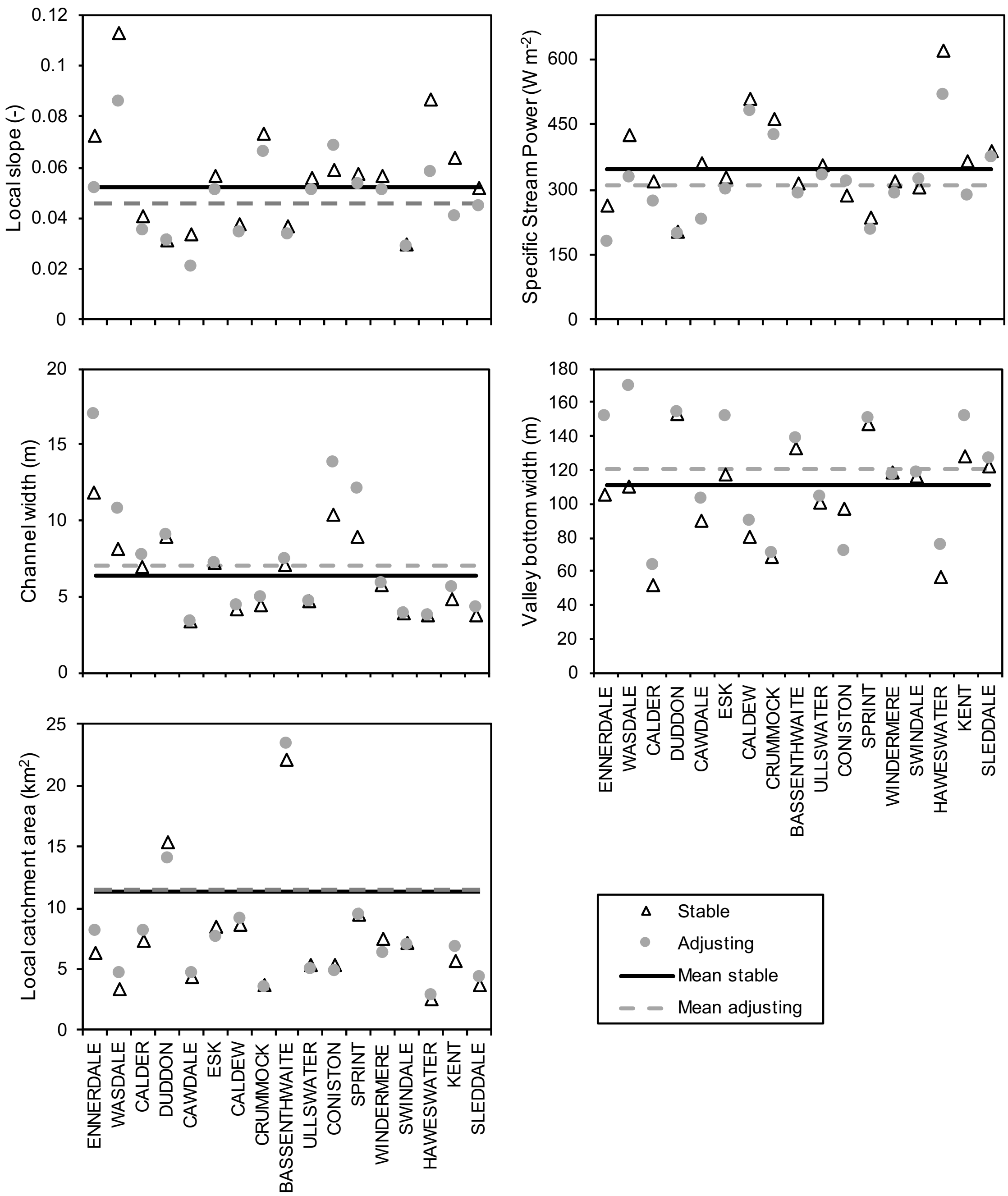


Figure 6.26. Mean geomorphic characteristics of adjustment and stable reaches for the 17 catchments in the Lake District study region. Black continuous line represents the regional mean geomorphic characteristics of stable reaches, and adjustment reaches are represented by the grey dashed line. Catchments are ranked from mean highest (Ennerdale) to lowest (Sleddale) adjusting catchments over the epochs studied.

6.6.3 The influence of geology, land cover and river management on planform adjustment and stability

Categorical variables (geology, land cover, and river management) are extracted and assigned to planform adjustment and stable reaches in Part 3 of the methodology (Fig. 6.1). This section explores the influence of geology, land cover and river management on the patterns of planform adjustment and stability over the last *c.* 150 years. It is hypothesised that planform adjustment length will vary according to the different geologies (e.g. fluvial, glacial sediments), land cover (e.g. acid grassland and woodland) and management (natural and modified river reaches).

6.6.3.1 River management

River management influences channel width, confinement, bank stability and potential for adjustment (Brookes, 1988; Sear et al., 2000; Downs and Gregory, 2004; Gregory, 2019). The highest frequency of adjustments and stable reaches were mapped in channels categorised as natural (n = 11185). In the study region, it was estimated that 33 % of the total river length studied was categorised as managed (Fig. 6.12), 12 % (n = 3588) of the total number of adjustments mapped over all time periods occurred on managed rivers.

Planform adjustments were recorded as occurring in a managed reach, if they overlaid a reach labelled as managed, and adjustments were categorised as semi-natural if it occurred on both managed and natural reaches. The mean length of channel affected by planform adjustment differs between managed, semi-natural and natural river reaches (Fig. 6.27). Bar adjustments affect a similar percentage (mean 0.8 $\pm$ 1.6 %) of channel length in managed, semi-natural and natural channels (no statistical differences) (Fig. 6.27). Similarly, the mean percentage of channel length categorised as width adjustment (3.7 $\pm$ 5 %) showed no statistical differences between the degrees of management. In contrast, statistical differences were identified between the mean adjustment length of bend adjustments, boundary adjustments and stable reaches between natural, semi-natural and managed channel reaches across the full dataset (Fig. 6.27).

Boundary and bend adjustments are longest in managed channels (Fig. 6.27). The mean percentage length of channel mapped as stable is also shortest (mean 7.3 ± 16.5 %) in managed systems compared to natural and semi-natural channels (Fig. 6.27). In managed rivers, channelization can cause local changes in stream power which can enhance erosion and deposition, which in turn necessitates channel changes to restore a natural equilibrium (Darby and Thorne, 1992). These processes may be progressive and can move the system to a threshold, which when crossed can trigger a sudden planform adjustment (e.g. avulsion) and explain the larger length of boundary adjustments and shorter length of stable reaches observed in managed reaches (Fig. 6.27).

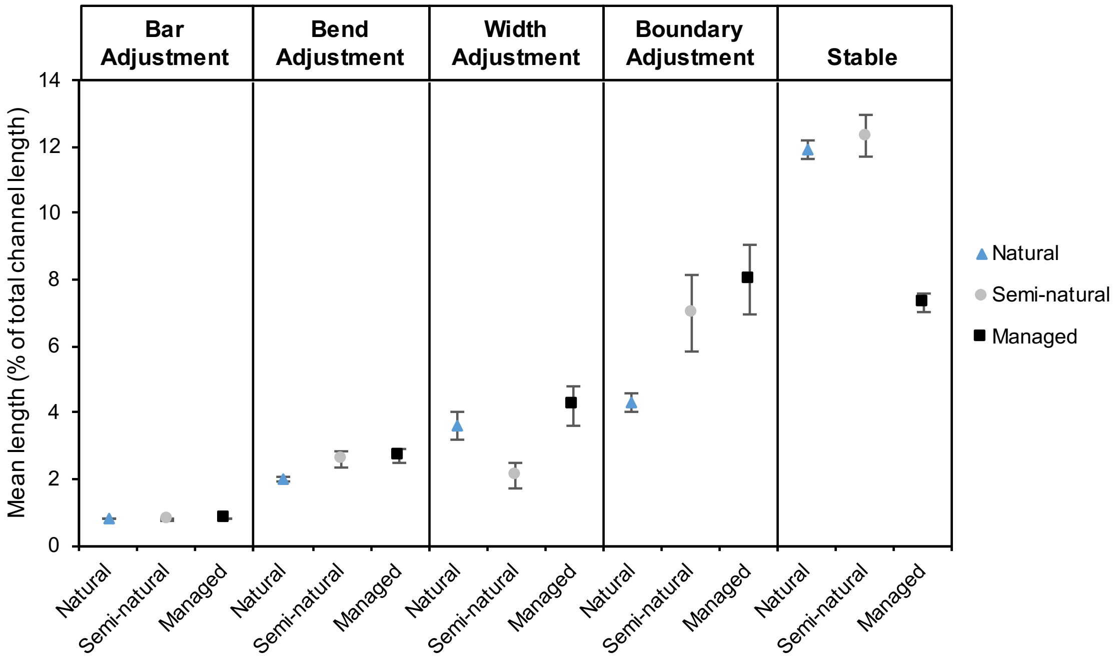


Figure 6.27. Mean and standard error of channel length affected by adjustment or stable reach (%) in managed, semi-natural and managed channels for all catchments.

Across the 17 catchments studied the percentage of channel length affected by adjustment in natural, semi-natural and managed reaches varies (Fig. 6.28). For example, in the Ennerdale, Wasdale and Coniston catchments adjustment length is factor of four greater than the regional mean adjustment length in managed channels (Fig 6.28). In contrast, natural and semi-natural reaches were categorised as having the mean longest length of stable reaches in the most stable catchments: Sprint, Haweswater, Kent and Sleddale (Fig. 6.28). The length of adjustment varies between the catchments because of the local catchment characteristics (e.g. slope, valley bottom width and sediment supply), as well as the type of channel management or anthropogenic activity. For example, adjustments observed in the Coniston catchment were influenced by an increased sediment supply from mining activities from Coniston Copper works. This analysis highlights that river behaviour has between catchment variability across the upland in response to anthropogenic activity (Fig. 6.28).

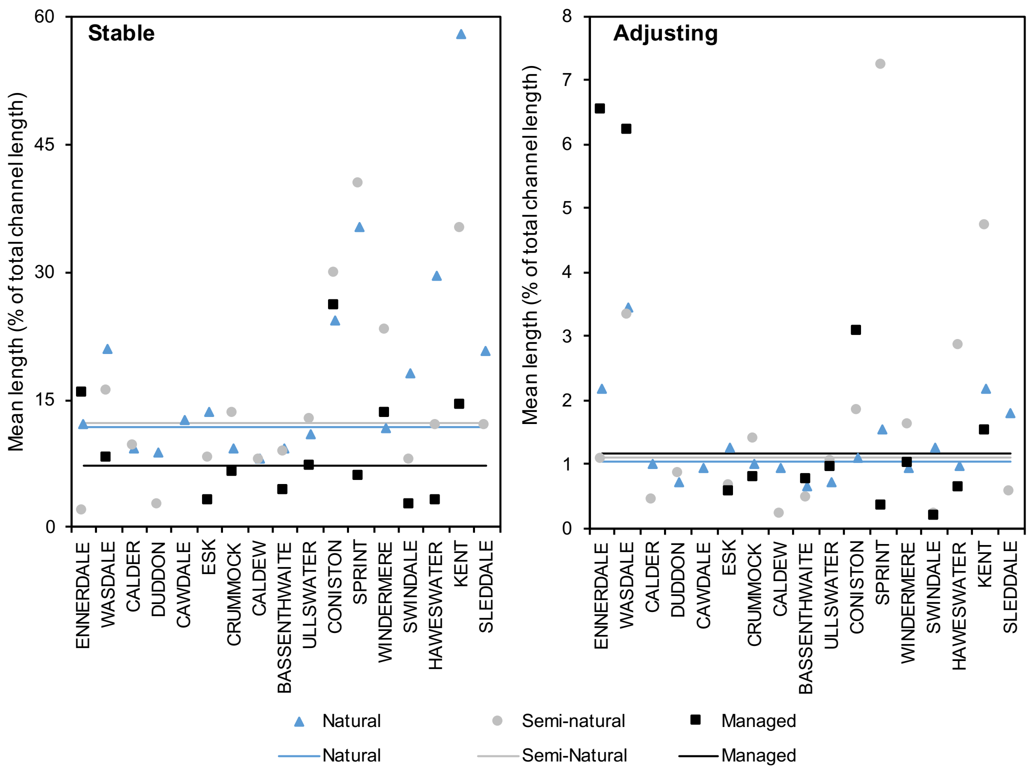


Figure 6.28. Mean length of stable or adjusting reach (%) by catchment for natural, semi natural and managed channels. Continuous lines represent the mean stable and adjustment length across the full dataset. Catchments are ordered by the mean highest (Ennerdale) to lowest (Sleddale) adjustment (%) across all time epochs.

6.6.3.2 Land cover

Land cover influences surface runoff and sediment availability to a channel, and therefore the potential for adjustment (Millar, 2000; Crosota and Saleh, 2011; Vargas-Luna et al., 2019). It is hypothesised that planform adjustment length will vary in urban, acid grassland and organic land uses where surface sediments can easily be eroded and delivered to the channel.

There were statistically significant differences between the mean adjustment and stable reach length for land cover categories. Acid grassland is the dominant land cover in the Lake District region, therefore the highest frequency (n = 18006, 61 %) of planform adjustments were mapped here. The mean length of adjustment on acid grassland was 1 ± 2 % of the total channel length. Planform adjustments were longest in arable and horticulture (3.5 ± 4 %). Planform stability was longest in neutral grassland (13 ± 23 %), broadleaf woodland (11.5 ± 22 %) and suburban areas (11 ± 17 %). The results indicate that there is variability in planform adjustment and stability length by land cover. Figure 6.29 displays the catchment to catchment variability in the mean length of stable and adjusting reaches for each land cover (Fig. 6.29). The correlation between land cover and adjustment and stability on a catchment by catchment basis is harder to define as land cover is spatially variable across the upland region. For example, acid grassland is present across all catchments, however the mean adjustment length varies from 0.7 ± 0.7 % (Cawdale) to a maximum length of 3.3 ± 7.2% (Coniston), (Fig. 6.29). Stable reach length also varies in acid grassland from 6.7 ± 6.3 % (Duddon) to 40 ± 40 % (Kent), (Fig. 6.29). This highlights that land cover alone is not a suitable predictor of planform adjustment and stability across multiple catchments in a region.

6.6.3.3 Geology

Geology partly influences the availability, type and erodibility of sediment and therefore influences the type and length of planform adjustment (Schumm, 2005). The bedrock and superficial geology is highly varied across the upland region and therefore it is difficult to use as a discriminatory variable for determining planform adjustment or stability. For example, the highest frequency of adjustment and stable reaches mapped over all time periods were on the Skiddaw group (n = 9159, 31 %) and Borrowdale Volcanic group (n = 16191, 54 %), two of the dominant bedrock geologies covering an area of 938 km^2, 75 % of the study region.

Planform adjustment length is hypothesised to vary between the different superficial geologies. Statistically significant differences were present between the length of adjustment and stable reaches between the superficial geology categories. The highest frequency (n = 10763, 65 %) of adjustments occurred in fluvial deposits in higher order channels, this is expected as planform adjustments involve the erosion, transfer and deposition of sediment from river channel bed and banks. The longest planform adjustments recorded occurred in mass movement deposits (mean length 1.3 ± 2.7 % (Fig. 6.30). Mass movements provide an additional source of sediment to the channel, which can redirect the flow and instigate longer length planform adjustments such as width or major boundary adjustments.

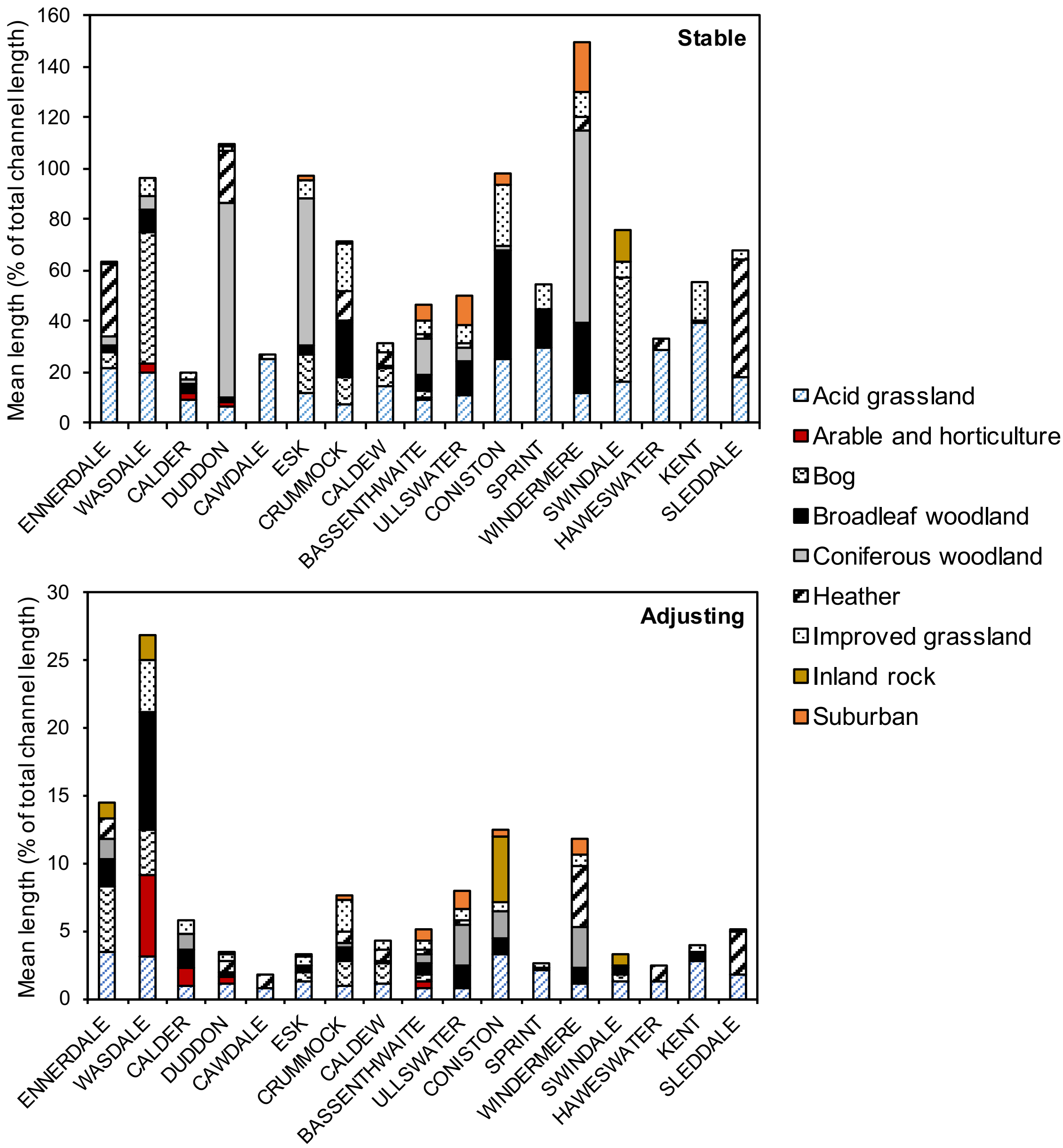


Figure 6.29. Mean length of stable and adjustment reaches (as a % of the total channel length) for the land cover types across the 17 catchments studied in the Lake District. Catchments ordered from highest adjusting (Ennerdale) to lowest adjusting (Sleddale) over all time epochs studied.

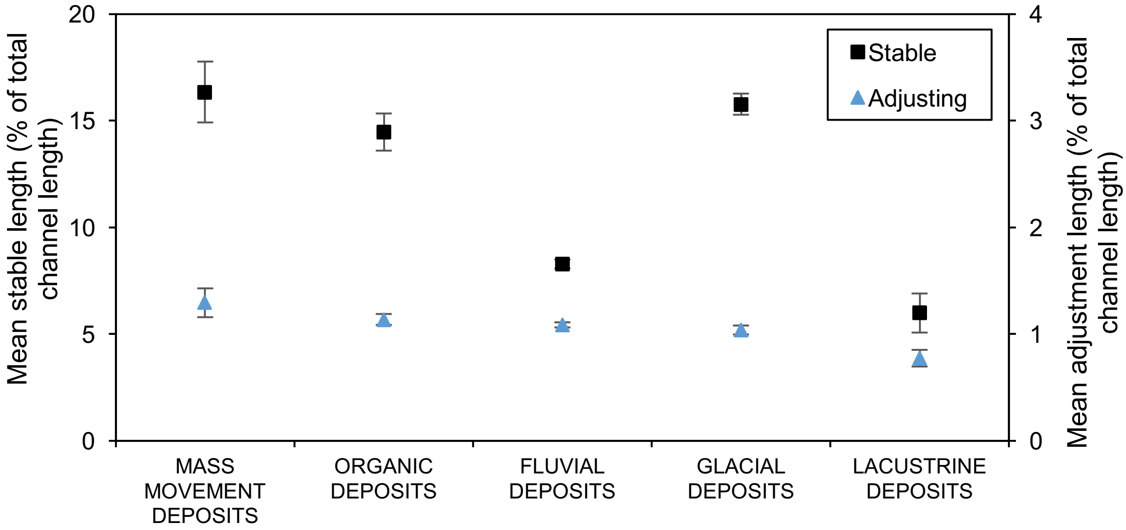


Figure 6.30. Mean adjustment and stable reach length (as % of the total channel length) and standard error bars for the superficial geologies in the Lake District study region.

However, mass movements deposits were also associated with the mean longest length of stable reaches (16 ± 28 %). Sediment delivered from mass movements may be reworked in the channel immediately after the event and therefore evidence of their impact on river planform may be short-lived and not be captured in the available snapshot of river planform from the available historic data explaining this relationship.

Areas dominated by organic deposits were expected to show longer stretches of channel experiencing adjustment due to a high supply of fine sediment (Evans and Warburton, 2001). The results of this analysis show organic deposits displayed a high percentage of stability (Fig. 6.30). Glacial deposits have the second highest mean percentage (15 ± 29 %) of channel mapped as stable (Fig. 6.30), this is because coarse glacial sediments can confine the channel in upper headwaters and therefore restrict lateral 2D adjustment.

There is considerable variation in the length of planform adjustment and stability between the 17 catchments (Fig. 6.31), therefore making the influence of superficial geology alone an unsuitable discriminatory variable of planform adjustment and stability. For example, in glacial deposits stable reach length varies from 10 ± 23 % (Bassenthwaite) to 88 ± 29 % (Cawdale) and adjustment reach length varies from 0.5 ± 1 % (Duddon) to

5.7 ± 23 % (Sleddale), (Fig. 6.31). Therefore, the influence of geology on planform adjustment and stability varies on a catchment by catchment basis.

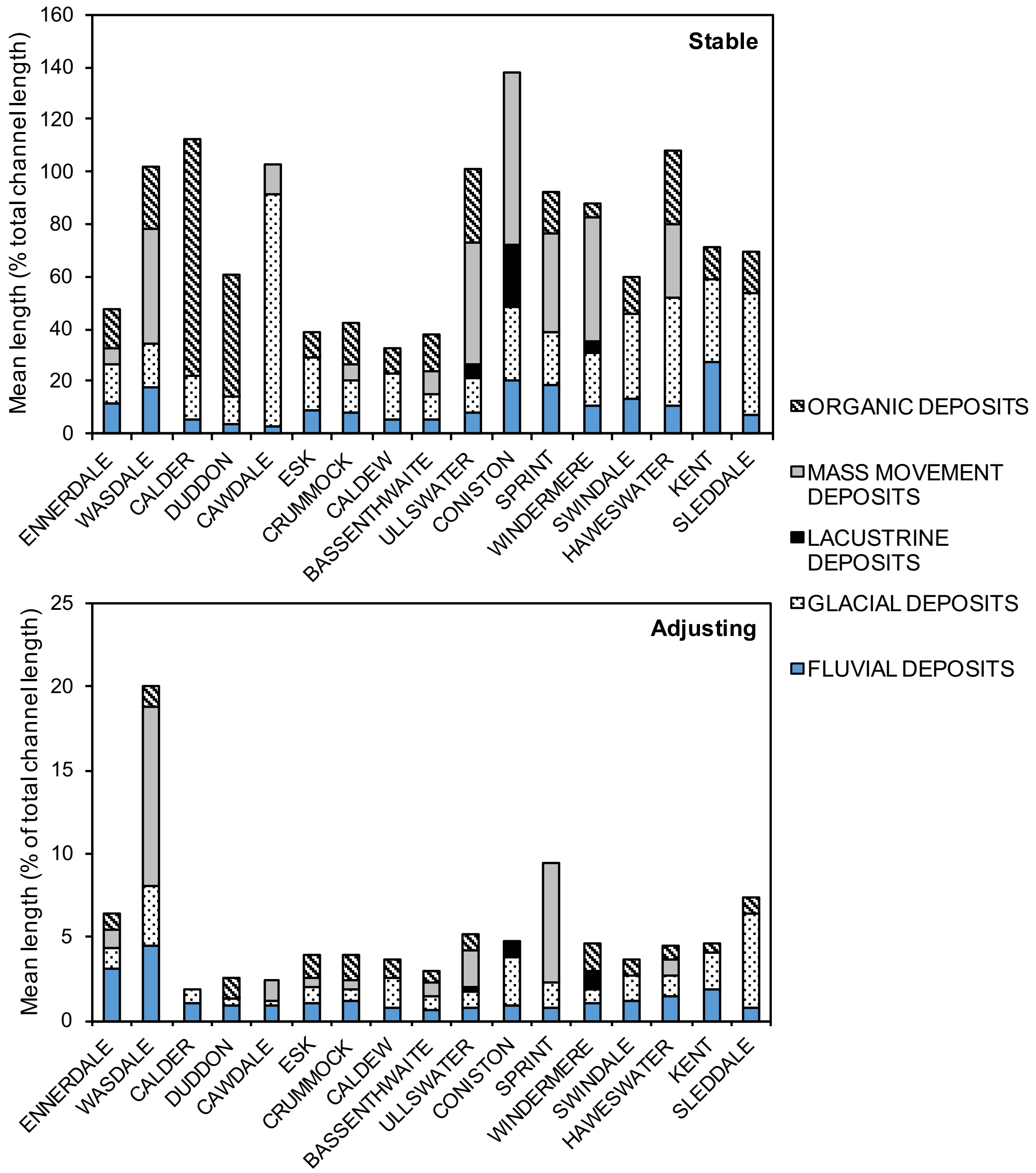


Figure 6.31. Mean length of stable and adjustment reaches (as a % of the total channel length) for the superficial geologies across the 17 catchments studied in the Lake District. Catchments ordered from highest adjusting (Ennerdale) to lowest adjusting (Sleddale) over all time epochs studied.

6.6.4 Summary of the geomorphic characteristics of adjustment and stable reaches

Section 6.6 has considered the geomorphic characteristics (stream power, channel width, valley width, slope, catchment area, geology, land cover and management) influencing the location and extent of planform adjustment and stability mapped in the Lake District study region. Valley bottom width and channel width were identified as important variables influencing the type of planform adjustments (Tables 6.7, 6.8). River management affects the length of boundary and bend adjustments and stable reaches (Fig. 6.27). However, at the regional scale the influence of land cover and geology on planform adjustment and stability is harder to define. Section 6.7 discusses the data collected and summarises the research findings.

6.7 Discussion: a multiple catchment scale assessment of the patterns and controls of historic river planform adjustment

Upland rivers are dynamic geomorphic systems (Newson, 1989; Lewin et al., 1977; Hooke and Redmond, 1989a) and across the 17 catchments studied in the Lake District upland region over the period 1860s - 2010, 21 % (128 km) of channels studied showed evidence of adjustment. Section 6.7.1 firstly explores the spatial patterns and geomorphic characteristics of planform adjustments through the Upland Sediment Cascade (USC), and considers the geomorphic controls. The temporal patterns of planform adjustment and stability over the last *c.* 150 years (Section 6.7.2) are then discussed.

6.7.1 Patterns and controls of planform adjustment and stability

6.7.1.1 Spatial patterns of adjustment through the Upland Sediment Cascade (USC)

The USC provides an important framework for interpreting the spatial patterns of planform adjustment and sediment continuity observed across the Lake District. Figure 6.32 presents a modified version of the USC framework presented in Chapter 2 and illustrates planform stability and the dominant geomorphic characteristics in the zones of the USC identified in this research. Low order channels in the production zone of the USC have mountain torrent, cascade or step pool typologies, with narrow channel widths, high specific stream powers and are topographically confined making them 'resistant' to lateral adjustment (Brunsden and Thornes, 1979; Sear et al., 2003; Fryirs et al., 2009;

Thoms et al., 2018; Piégay et al., 2018; Fuller et al., 2019b). In the Lake District headwaters, rivers flow through steep confined bedrock channels (Figs 6.5, 6.7), gorges or glacial sediments which alternate with locally unconfined alluvial reaches (Harvey, 1997). Second order channels had the narrowest mean channel widths (3 ± 3 m) and mean valley bottom widths (27 ± 70 m), the mean steepest channel slopes (0.13 ± 0.09) and high specific stream powers (630 ± 430 W m^{-2}). Bar adjustments were the most frequent forms of sediment transfer (n = 2877, 85 % of total number of adjustments) in second order channels mapped over all time periods. Where the channel becomes locally unconfined bend, bar and width adjustments were present (Figs. 6.21, 6.32). However, regionally, the production zone showed relative planform stability, and second order channels had the highest percentage of channel length mapped as 2D stable over the last 150 years (mean stable length of second order channels 1860s-2010: 89 ± 16 %), demonstrating a high level of sediment continuity.

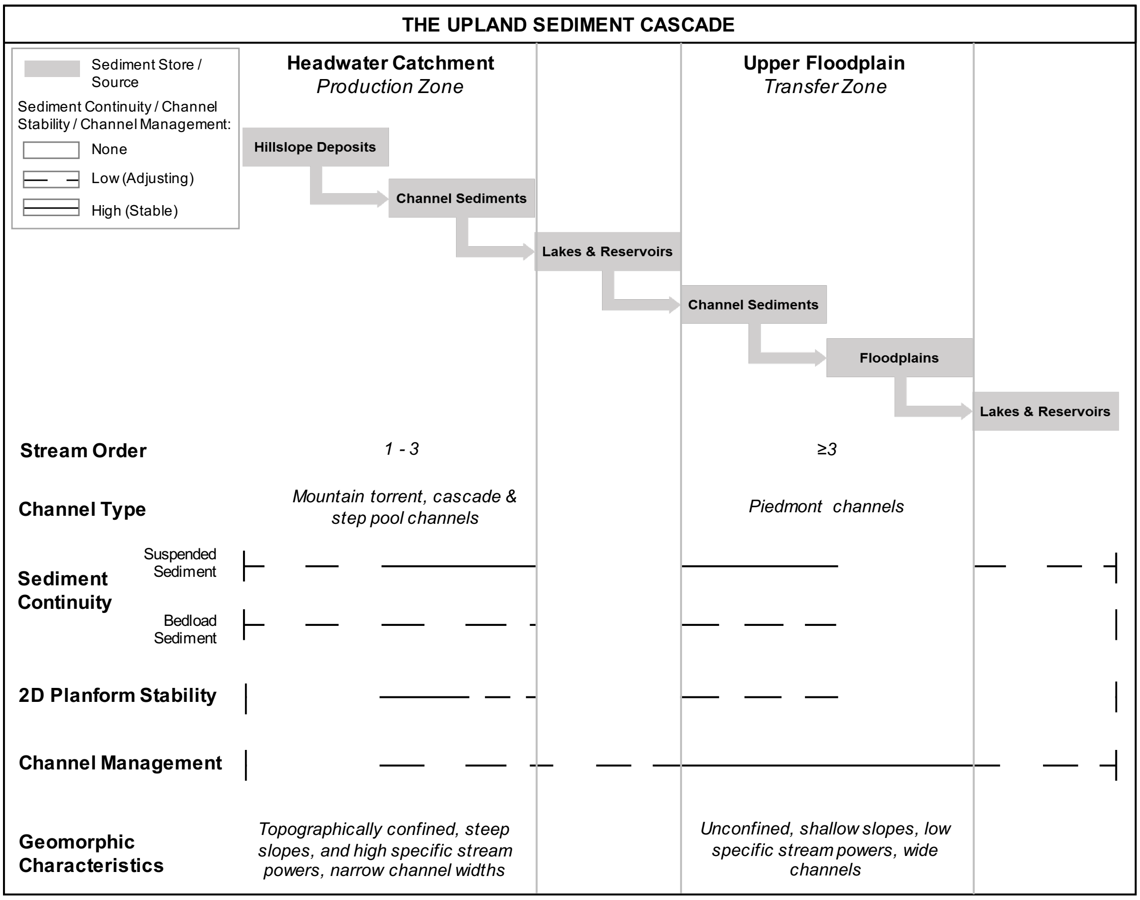


Figure 6.32. Upland sediment cascade displaying 2D planform stability, channel management and the geomorphic characteristics in each zone identified in this research.

In the lower reaches of the production zone (e.g. third order channels), in natural systems, where rivers enter lakes there are well-developed lakehead deltas and alluvial fans (Hay, 1926; Harvey, 1997; Schillereff et al., 2016; Chiverrell et al., 2019). Here, there is an increase in valley bottom width, slope decreases and there is a local decrease in sediment continuity (Fig. 6.32). This results in local sediment deposition, this creates a local increase in bed slope which can instigate planform adjustments such as avulsions (Jones and Schumm, 1999). For example, in the Wasdale catchments boundary adjustments were identified upstream of Wast Water (Chapter 5) over the 1860s-1950s period. In the Ennerdale 2010 air photograph, there is also evidence of palaeo-channels in the lakehead alluvial delta (Fig 6.33) indicating the river historically avulsed and occupied a different position on the floodplain. These palaeo-channels were not active in the 1860s historic map (Fig 6.33) or intermediate epochs studied (e.g. 1950s, 1980, 1995, 2004), indicating river activity in the lakehead delta >150 years ago. Therefore, in the lower reaches of the headwater production zone, channels can display a local decrease in sediment continuity (Fig. 6.32).

Regionally, second order channels in catchment headwaters showed similar geomorphic characteristics and local planform stability, however, there was evidence of local catchment and reach scale variability in the Lake District. For example, in the Coniston catchment, second order channels had the highest percentage of channel length affected by adjustment (mean length 3.6 ± 8 %) and largest channel widths (mean 8 ± 11 m) (Fig. 6.8). This local variability is attributed to Coniston Copper mine workings (NGR SD 289 985). Mining activities can alter catchment scale sediment dynamics by delivering large volumes of coarse and fine sediment, 'exoslugs', to the stream network through excavation works or from spoil heaps (Lewin et al., 1983; Knighton, 1989; Macklin, 1997; Bertrand and Liébault, 2019). This can result in channel widening and sediment aggradation which can be transported as megaslugs (Church and Jones, 1982; Hoey, 1992; Nicholas et al., 1995). Figure 6.34B shows Levers Water Beck a second order channel connected to spoil heaps from the Coniston Copper works, providing a major source of sediment. Channel width in Levers Water Beck is a factor of three greater than the second order neighbouring channels (e.g. Low Water Beck) due to enhanced sediment delivery from mining waste (Fig. 6.34B).

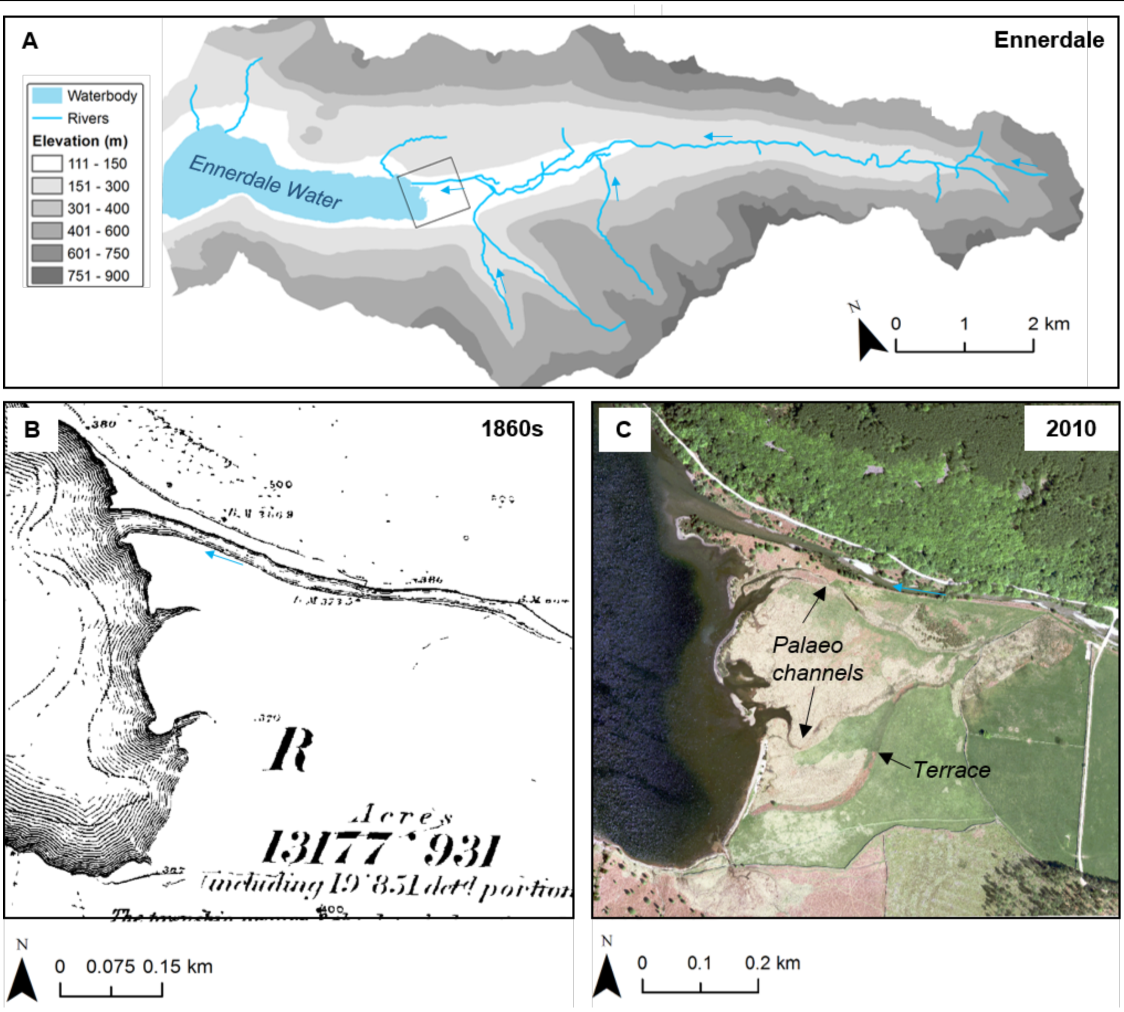


Figure 6.33. Relict channels in the lakehead alluvial fan in the Ennerdale catchment. Blue arrows indicate flow direction. (A) Ennerdale catchment elevation, black square indicates location of (B) and (C). (B) 1860s historic map of lakehead delta (source: Ordnance Survey, 2015). (C) 2010 air photo (source: Bluesky International Ltd., 2015) of lakehead delta, palaeo-channels and terrace.

Downstream of the confluence between Levers Water and Low Water Beck further spoil heaps are present which confine the channel and supply sediment (Fig. 6.34C). The impact of the increased sediment supply is observed where the channel becomes locally unconfined and slope decreases, and therefore sediment is deposited (Fig. 6.34C). Typically, the extent of the sedimentation zone decreases where the channel becomes topographically confined, slope and stream power increases and bedrock outcrops are present, creating a local increase in transport capacity (Fig. 6.34C). This example shows that the spatial pattern of sediment continuity through the USC headwaters is influenced by local reach scale anthropogenic activity, as well as wider topographic controls (e.g. confinement and slope).

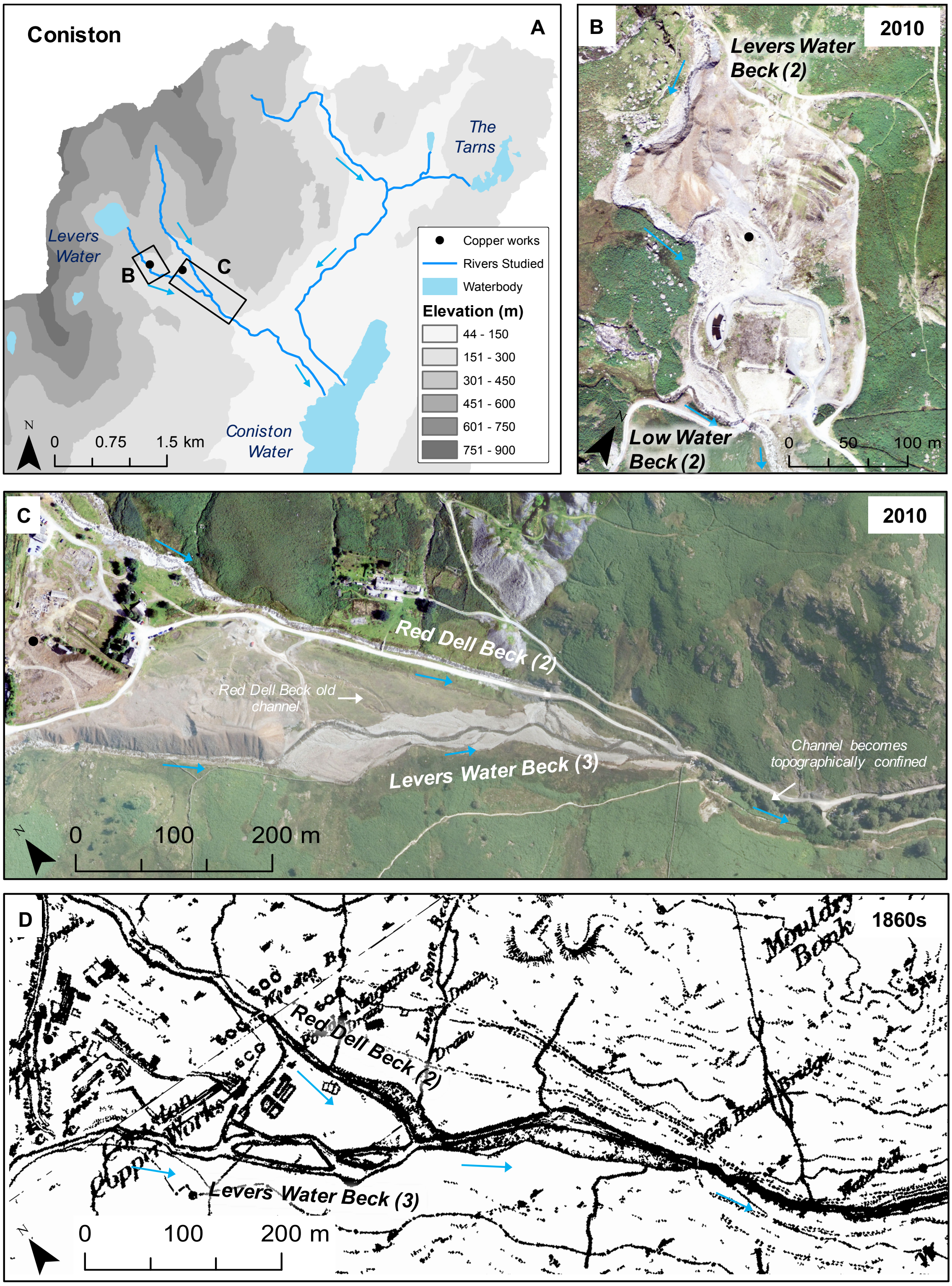


Figure 6.34. Anthropogenic modification to sediment continuity example: Coniston catchment. A) Rivers studied and topography of the headwaters of the Coniston catchment South, Lake District, UK. B, C and D show examples of river planform near Coniston Copper works from the 2010 air photograph (source: Digimap, 2017) and the OS County series 1860s historic map. Arrows indicate flow direction, numbers at the end of the river names indicate Strahler (1952, 1957) stream order.

In the transfer zone (Fig. 6.32), sediment continuity and patterns of planform adjustment differ from those of the production zone as the channel gradient decreases, floodplain width increases and the channel becomes unconfined, allowing greater channel floodplain interaction. The highest frequency of planform adjustments observed in the Lake District study region were in third order channels (number of adjustments = 9252, 56 % of total number of adjustments) over all time periods. High order (e.g. fourth, fifth and sixth order) channels in the transfer zone in the Lake District study region had the highest percentage of channel length mapped as managed (Figs. 6.14, 6.15). Channel management is expected to influence the potential for planform adjustment and sediment continuity by altering the flow regime (e.g. through flow regulation, downstream of lakes), sediment supply and restricting lateral adjustment e.g. by reinforcing banks (Surian and Rinaldi, 2003; Downs and Gregory, 2004). The following section will explore the impact of channel management in the USC.

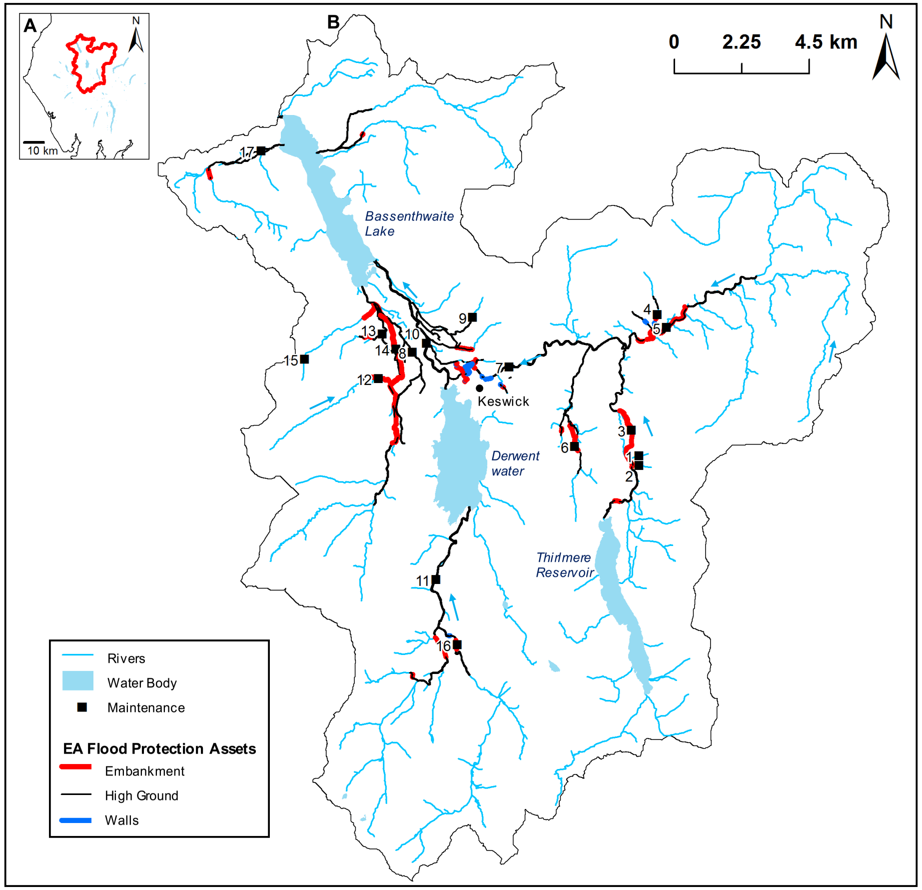
6.7.1.2 Impact of channel management on planform adjustment and stability through the Upland Sediment Cascade

In the Lake District study region, the percentage of channel length mapped as managed increases with stream order through the USC (Fig. 6.15). For example, the mean percentage of channel length mapped as managed in second order channels: 5 ± 18 %, in third order channels 21 ± 32 %, in fourth order channels 73 ± 32 %, in fifth order channels 92 ± 23 %, and for the two sixth order channels studied: 100 %.

The Bassenthwaite catchment has the best documentation of historic channel management from the Cumberland River Board Authority reports and Environment Agency asset management records and therefore provides an example of the type and spatial extent of river management activities (Fig. 6.35). Figure 6.35 highlights that management is concentrated in high order channels in the transfer zone and anthropogenic activities involve bank reinforcement and gravel management. For example, flood walls surround the River Greta near Keswick to prevent flooding, and gravel management (dredging) takes place on over 17 rivers in the catchment to increase channel capacity during flood events (Fig. 6.35). A high percentage of river management in the Bassenthwaite catchment (45 % of rivers and streams studied are managed) could explain why over all time periods the total percentage of channel length mapped as adjusting is low (mean adjustment length 13 ± 6.5 %), (Fig. 6.36). In comparison, more natural catchments, with a lower percentage of management display a higher percentage of rivers and streams mapped as adjusting (Fig 6.36). For example, in the Ennerdale catchment, 6 % of the rivers and streams studied are managed (relatively natural catchment) and the adjustment percentage was high over all time periods (mean adjustment length 26 ± 6.2 %) compared to the other catchments (Fig 6.36).

Figure 6.36 summarises the percentage of channel length mapped as adjusting and the total channel length mapped as managed. The Bassenthwaite, Ullswater, Coniston, Sprint, Windermere and Kent catchments have >40 % of channels mapped as managed (Fig. 6.36). These catchments have less than 13 % of the total channel length mapped as adjusting over all epochs, indicating that local management has contributed to local 2D channel stability and the patterns observed.

River management has traditionally focused on stabilising adjusting rivers in the transfer zone of the USC (Brookes, 1988). Regionally, the length of stable reaches (mean length 7.3 ± 16.5 %) is shortest in managed channels compared to natural reaches (mean length 12 ± 25 %) (Fig. 6.27). Lake District rivers have high specific stream powers (mean 460 ± 410 W m^{-2}) and therefore in areas where rivers are anthropogenically stabilised, high stream powers will be concentrated on the channel bed and banks which can lead to locally enhanced erosion of sediment and planform adjustment (Brookes, 1985). This indicates that channel management is not always efficient at fixing the problem and channel instabilities persist. This is especially true if managed river reaches are not maintained as systems adjust to restore a pre-modified condition: a natural 're-wilding' process (Brookes, 1988; Fryirs and Brierley, 2016).



C

ID	River/Location	Management Type: Gravel Management	Vegetation Maintenance	Bank protection / repairs
1	Beckthorns	✓		
2	Fornside	✓		
3	St John's Beck	✓	✓	✓
4	Gatesghyll Beck	✓	✓	
5	River Glenderamackin	✓		✓
6	Naddle Beck	✓	✓	
7	River Greta	✓	✓	✓
8	Pow Beck	✓	✓	✓
9	Applethwaite	✓		
10 / 11	River Derwent	✓	✓	✓
12	Coledale Beck	✓		✓
13	Hallgarth Beck	✓		
14	Newlands Beck	✓	✓	✓
15	Chapel Beck	✓	✓	
16	Stonethwaite Beck	✓		✓
17	Dubwarth Beck	✓		✓

Figure 6.35. (A) Location of Bassenthwaite Lake catchment in north-west England. (B) Example of river management as documented in the Cumberland River Board Authority Reports (1950s – 1970s) and EA asset management data. The EA flood protection assets refer to features (embankments, high ground and walls) that have been maintained (by dredging, bank protection works and vegetation maintenance). Black squares indicate rivers continually maintained and documented in the Cumberland River Board Authority reports, numbers next to black square are summarised in C. (C) Types of river maintenance documented in the Cumberland River Board Authority reports.

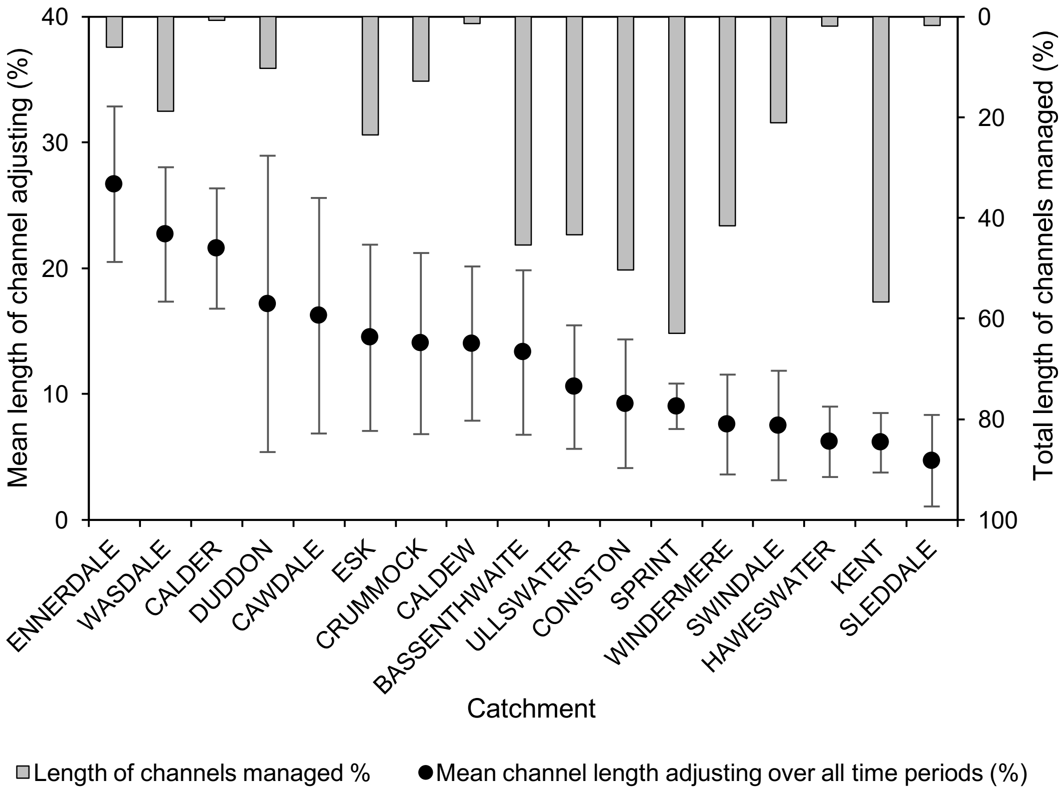


Figure 6.36. Mean channel length adjusting (%) over all time periods studied and standard deviation error bars plotted alongside the total length of channels mapped as managed (%) in the Lake District study catchments. Catchments ordered from highest adjusting (Ennerdale) to lowest adjusting (Sleddale) over all time epochs studied.

In managed channelized reaches, it was expected that planform adjustments will affect longer lengths of the channel in response to inappropriate river management. In the Lake District study region boundary adjustments had the longest length in managed channels (mean length 8 ± 12 %) compared to natural channels (mean length 4.3 ± 6 %). On upland rivers Tummel, Tay and Dee in Scotland, flood embankments are present and restrict adjustment, however, embankments are regularly breached, channels avulse and deposit sediment in response to extreme flood events (Gilvear and Winterbottom, 1992; Gilvear, 1993; Winterbottom, 2000). These examples demonstrate that major planform adjustments often occur in artificially confined reaches as channels adjust to restore a natural equilibrium. Similarly, the St John's Beck reach scale study (Chapter 4), showed significant river bank erosion, resulting in a 12 m increase in channel width in response to the extreme Storm Desmond flood, where the channel had been artificially confined and flood embankments disconnected the channel from the floodplain. Similar effects have been observed by Magilligan (1985), Nanson (1986), Butler and Malanson (1993), Lecce (1997), Fuller (2007, 2008), who all identified a concentration of erosion on constricted reaches. Therefore, although channel management can locally stabilise channels, it disrupts natural sediment continuity, which can prime the channel for major boundary adjustment in response to high magnitude flood events.

Anthropogenic activity can also directly cause planform adjustment (e.g. straightening and realignment). However, it is difficult to identify if planform adjustments are artificial or natural from historical records due to: the limited availability of documents on channel modification over the past 150 years, and that the sources used represent a 'snapshot' of river planform. Therefore, artificial adjustment may take place between historic map / air photograph survey and production dates, or pre-date the earliest historical maps (Winterbottom, 2000). In this analysis 144 planform adjustments were recorded as artificial over all time periods, these channels had clearly been straightened or reinforced by anthropogenic engineering near settlements, infrastructure or industry. For example, in the Coniston catchment Red Dell Beck, a second order channel, was artificially straightened, diverted and confined against the valley walls to allow room for a road to be built providing access to Coniston Copper works (Fig. 6.34).

The highest frequency of 'artificial' adjustments mapped in this study were recorded in the Bassenthwaite catchment (n = 58) and included river straightening, re-diversion and stabilisation providing another reason why the percentage of adjustment is relatively low over all time periods in this catchment (Fig 6.36). An example of river re-diversion in the Bassenthwaite catchment, is on Raise Beck (NGR NY 330 118), which was artificially diverted North (previously flowed South towards Grasmere) into Thirlmere Reservoir between 1920 and 1935 (Hindle, 1981; Huddleston, 1935) to ensure a continuous water supply to Thirlmere Reservoir (Fig. 6.37). Despite the difficulty in classifying adjustments as natural or artificial it is important to be aware that artificial adjustments take place at the reach scale on high and low order channels in the USC and can explain local patterns of planform adjustment and stability observed over the last *c.* 150 years.

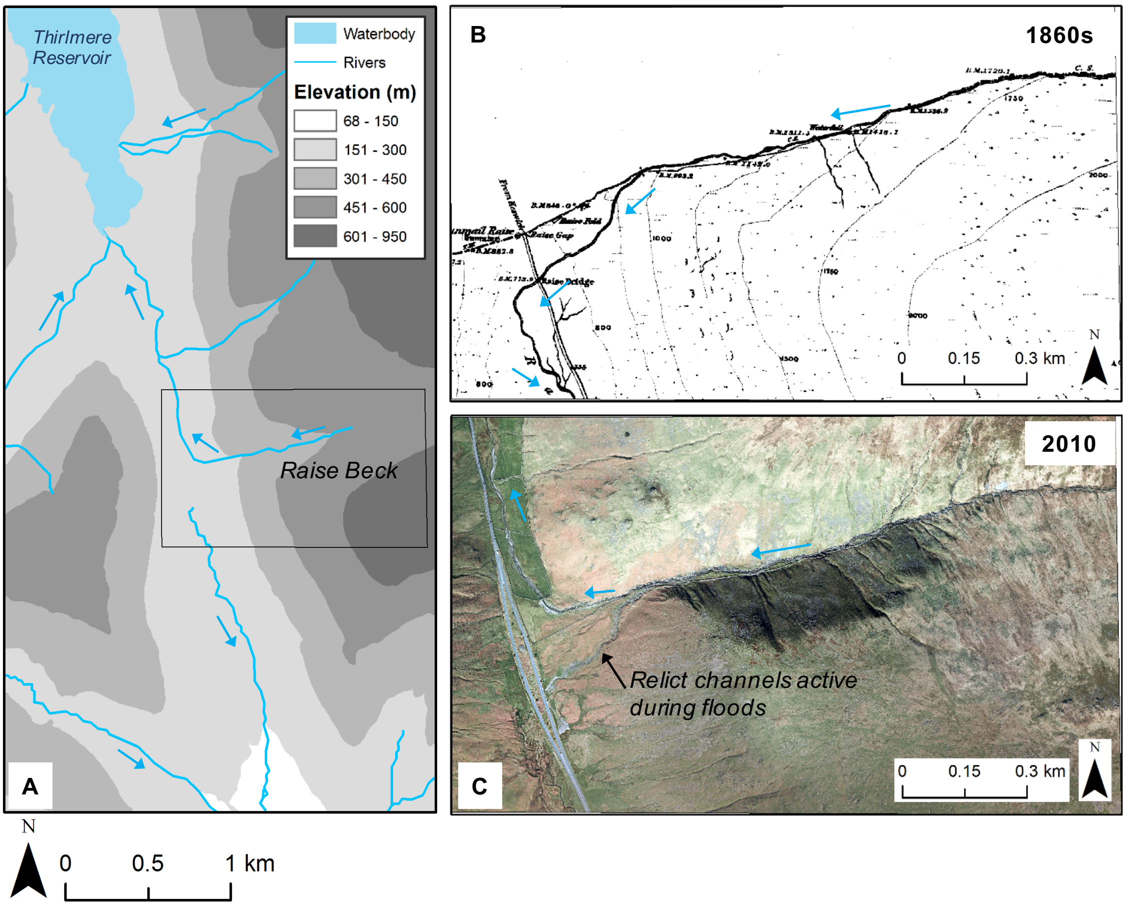
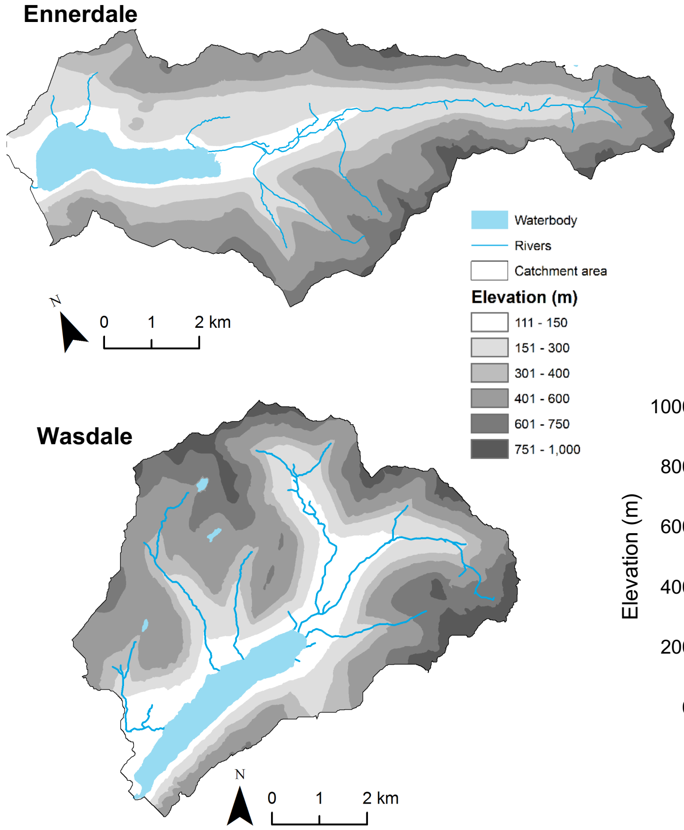


Figure 6.37. Artificial channel diversion on Raise Beck, blue arrows indicate flow direction. A) current flow direction into Thirlmere Reservoir, box highlights area of B and C. (B) 1860s historic map (source: Ordnance Survey, 2015), Raise Beck flowed south towards Grasmere. (C) 2010 air photograph (source: Bluesky International Ltd., 2015) showing current flow direction (north to Thirlmere) and old relict channels which become active during flood events (*c.f.* Johnson and Warburton, 2002).

6.7.1.3 Geomorphic controls on planform adjustment and stability through the USC

Valley bottom width and channel width were identified as important variables influencing the type of planform adjustment and stability observed regionally through the USC (Tables 6.7, 6.8). There were statistically significant differences between stable and adjusting reaches valley bottom width and channel width (Table 6.7). Stable reaches (n = 13377) had a mean channel width 6 ± 5 m, and valley bottom width 110 ± 170 m. In contrast, adjustment reaches (n = 16455) had a mean channel width 7 ± 6 m and valley bottom width 120 ± 190 m. Valley bottom width determines channel confinement creating space available for the channel to interact with the floodplains, therefore planform adjustments are more likely to occur in unconfined settings where the channel can erode the banks and laterally migrate (Schumm, 1977; Church, 1996; Ibisate et al., 2011; Fryirs et al., 2016; O'Brien et al., 2019).

Lisenby and Fryirs (2016) found catchment area to be an important variable influencing the location and extent of planform adjustments in three tributaries with similar form ratios in the Lockyer Valley, Australia. However, in the Lake District, catchment area was a poor predictor of planform adjustment across the 17 catchments and no statistically differences were identified between mean catchment area of stable and adjusting reaches (Table 6.6). This relationship is attributed to local variability in catchment form and relief ratio (Table 6.3). For example, the Ennerdale (catchment area = 44.1 km^2) and Wasdale catchments (catchment area = 45.4 km^2) have similar catchment areas and displayed persistent 2D planform adjustment over all time periods studied, however had very different catchment shapes (Table 6.4, Fig 6.38). The Ennerdale catchment is elongated (form ratio 0.22), with a relief ratio of 0.05. In the Ennerdale catchment planform adjustments had a mean catchment area of 8 ± 7 km^2 (Fig 6.38). In contrast, the Wasdale catchment has a bowl like shape (form ratio 0.56), is steeper (relief ratio 0.1) and adjustments had a mean catchment area of 5 ± 4 km^2 (Fig 6.38). This example shows that catchments with similar catchment areas can have very different shapes, and relief ratios and therefore using catchment area alone is a poor predictor of planform adjustment and stability at the multiple catchment, regional scale.



	Ennerdale	Wasdale
Catchment area (km²)	44.1	45.4
Relief ratio	0.045	0.101
Form ratio	0.22	0.56

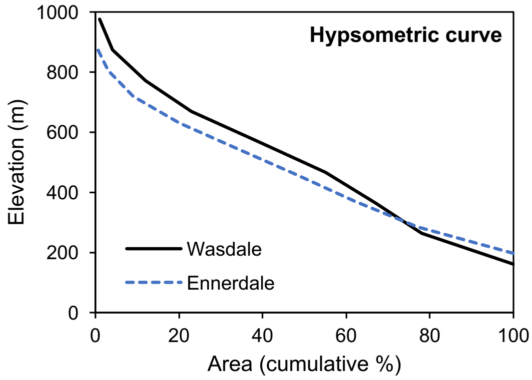


Figure 6.38. Example of variability in catchment form ratio, relief ratio and hypsometric curves for the Wasdale and Ennerdale catchments.

Geology and land cover influence the type, erodibility of sediment and potential for planform adjustment (Schumm, 2005). However, the geology and land cover is highly variable across the Lake District upland region and therefore it is difficult to use as a discriminatory variable for determining planform adjustment or stability at the regional scale (Figs. 6.29, 6.31). In-channel wood and log jams were not considered as a major control of planform adjustment in the Lake District upland study region as large upland forests were cleared during the Neolithic, Iron Age and Romano-British and medieval periods (Edwards and Whittington, 2001; Chiverrell, 2006; LDNPA, 2017) and more recent forestry (Forestry Commission c. 1919) is carefully manged to prevent wood entering low order tributaries. Catchment re-wilding and in-channel wood and logjam installation for natural flood management and river restoration projects have potential to influence future reach scale patterns of planform adjustment and stability (Grabowski et al., 2019).

Identifying a singular dominant control on planform adjustment and stability at the catchment and regional scale is unlikely. River planform adjustment and stability is influenced by multiple spatially variable exogenic and endogenic interacting factors (Bull, 1991). Planform adjustments also often occur in combination (e.g. bar and bend adjustments), 22 % of adjustments occurred in combination for 1860s – 2010 period (Fig. 6.39), and therefore it is difficult to identify a singular control for each type of adjustment. Instead, this research highlights that regionally, geological and glacial legacies in the Lake District have set the topographic conditions (confinement, U-shaped valleys, valley size, radial drainage pattern) and calibre and supply of sediment to rivers which determines the USC structure. Figure 6.40 summarises the dominant variables influencing planform adjustment and stability in the USC (e.g. slope, valley bottom width, channel width, geology, land cover, management) and their spatial variability in the Lake District upland region. The USC provides a useful general framework for understanding the patterns and controls of planform adjustment and stability, however, this does not explain the anomalies in local planform adjustment and stability on a catchment by catchment basis over all time periods.

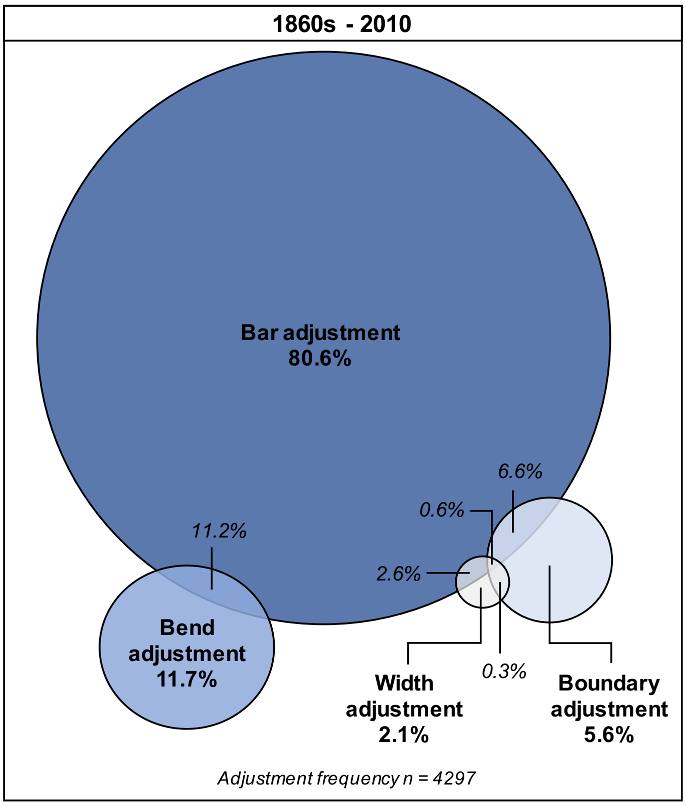


Figure 6.39. Venn diagram showing total percentage of adjustments for each category (bold) and combined adjustments (italics) for the full period of analysis (1860s – 2010), for all rivers in the Lake District study region.

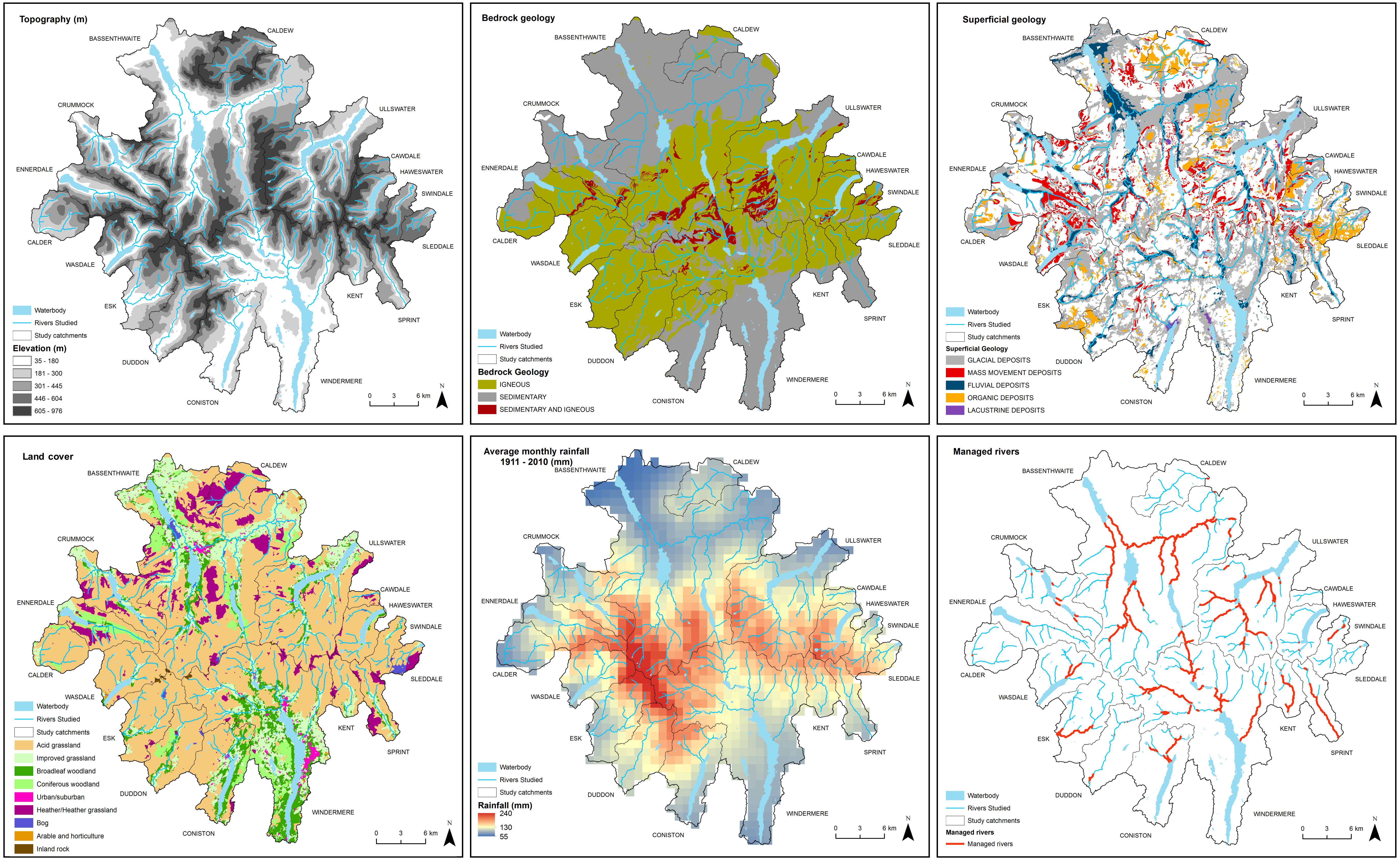


Figure 6.40. Regional geomorphic characteristics across the Lake District upland study region: topography, bedrock and superficial geology, land cover, average monthly rainfall and managed rivers.

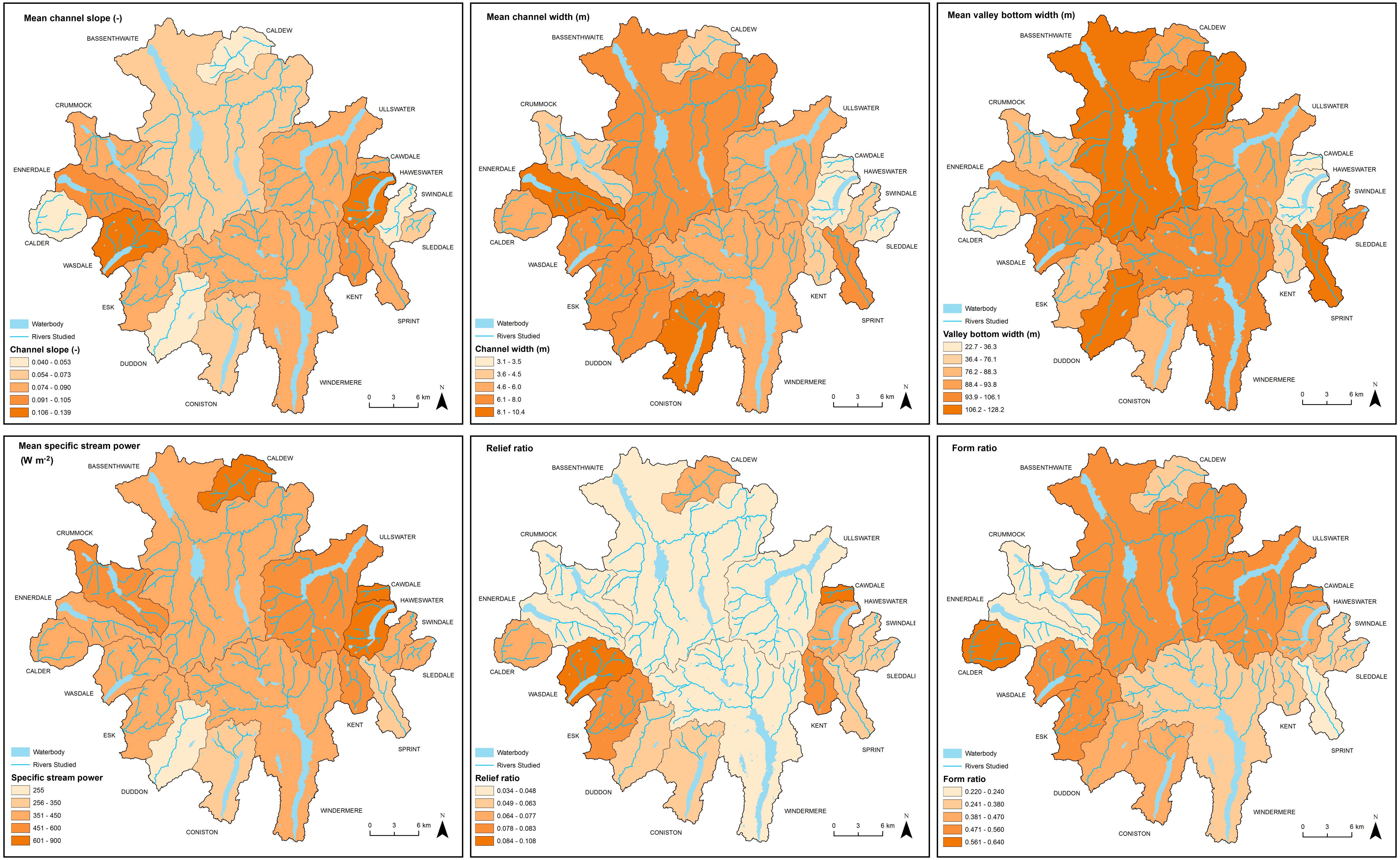


Figure 6.40. Continued: regional geomorphic characteristics across the Lake District upland study region: mean slope, specific stream power, channel width, valley bottom width (extracted from SPs); form and relief ratio.

6.7.1.4 Why do some catchments display persistent planform adjustment or stability?

The Ennerdale and Wasdale catchments showed persistent adjustment and have the highest mean percentage of channel length mapped as adjusting over the last *c.* 150 years (Figs. 6.23, 6.24, 6.40, 6.41). These catchments are located in the west of the Lake District study region overlying the Borrowdale Volcanics, Ordovician felsic plutonic suite and Skiddaw group bedrock geologies (Fig. 6.10). These catchments displayed statistical differences in the geomorphic characteristics (slope, channel width and specific stream power) compared to the other catchments studied (Table 6.7; Figs. 6.5-6.9). For example, the Ennerdale and Wasdale catchments had the steepest channel slopes in the headwaters and low channel slopes and specific stream power values in third, fourth and fifth order channels (Figs. 6.5, 6.9). These catchments also had the highest percentage of catchment area occupied by mass wasting events (17 % of the Ennerdale catchment area and 14 % of the Wasdale catchment area), (Fig. 6.11). Planform adjustment length was longest in mass movement deposits (mean adjustment length = 11 ± 10 %) in the Wasdale catchment (Fig. 6.31). It is likely that sediment is delivered from mass wasting events where the channel is coupled to the hillslopes in the headwaters, and the high specific stream powers enable this material to be transported downstream. As sediment is transported downstream, it is deposited where slope and specific stream power decreases and valley bottom width increases. This can cause intrinsic thresholds to be crossed, for example, sediment deposition can lead to local changes in channel gradient which may locally increase stream power and therefore the potential for adjustment (Bull, 1991; Brewer and Lewin, 1998). Therefore, sediment supply from mass wasting events may represent a triggering mechanism explaining the high percentage of channel length mapped as adjusting in the Wasdale and Ennerdale catchments.

However, the Ennerdale and Wasdale catchments might also be responding to exogenic changes in climate and flood frequency or anthropogenic activity. As no flow gauges are present in the Wasdale or Ennerdale catchment upstream of the lakes it is difficult to assess the impact of flood events on local catchment scale planform stability. These catchments are located on the west of the Lake District upland region, and therefore are influenced by more vigorous westerly airflows from the Atlantic and therefore wetter winters (Rodwell et al., 1999; Rodwell and Folland, 2002; Barker et al., 2004; Pattison and Lane, 2012), (Fig. 6.40). Wetter winters can lead to high pore water pressures in catchment hillslopes and influence the frequency of mass wasting events (Warburton et al., 2008). Anthropogenic modifications (embankments, bank reinforcements) are present in both Ennerdale (Oyedotun, 2011) and the Wasdale catchment (Haycock and Skinner, 2004), however, planform adjustments are still present due to the high-energy nature of these systems (Figs. 6.9, 6.24).

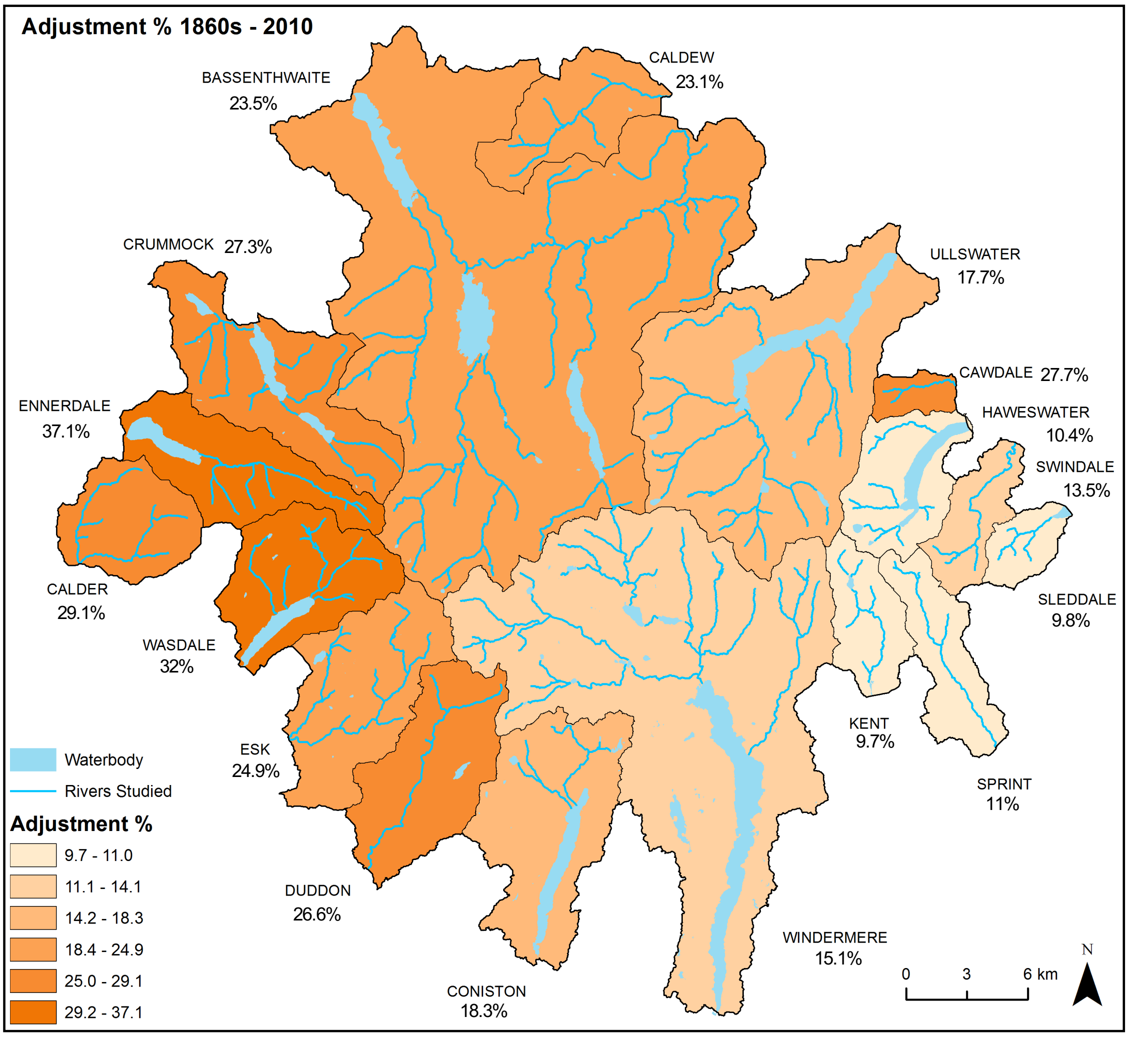


Figure 6.41. Choropleth map displaying the total length of channels adjusting (%) for 1860s – 2010 period by catchment in the Lake District study region.

In contrast, Kent, Haweswater and Sleddale showed persistent 2D stability over all time periods (Figs. 6.21, 6.41). These catchments are located in the east of the Lake District study region and are underlain by Borrowdale Volcanics, Borrowdale sill suite and Coniston group bedrock geologies. The catchments all have reservoirs (Haweswater Reservoir, Wet Sleddale Reservoir and Kentmere Reservoir) therefore the catchments will be influenced by flow regulation. The Kent catchment has the highest percentage of channel mapped as managed (57 %), compared to the Haweswater (2 %) and Sleddale (2 %) catchments. Rivers in the Kent catchment have been reinforced and embankments are present in response to the legacy of water mills and land drainage for agriculture in the catchment (Orr et al., 2000; Soar et al., 2017).

Haweswater had the steepest channel slopes (mean slopes 0.14 ± 0.11), with the highest number of statistical differences in slope compared to the other catchments (Fig 6.5). Channel widths were also narrow, resulting in high specific stream powers (mean 520 ± 260 W m^{-2}). This can lead to high levels of sediment continuity explaining why channels display patterns of persistent 2D stability over the last *c.* 150 years. The Haweswater catchment also has the second narrowest mean valley bottom widths (70 ± 50 m), and channels are topographically confined by bedrock or glacial sediments restricting lateral adjustment. In contrast, the Sleddale geomorphic characteristics (slope, valley bottom width) showed fewer statistical differences between the geomorphic characteristics between the catchments (Section 6.4), but the land cover is dominated by organic deposits and heather. Upland catchments dominated with organic deposits and heather have been reported as some of the most actively eroding catchments in the UK (Stott, 1995; Evans et al., 2006). However, this analysis shows that catchments dominated with this land use type showed relative 2D stability in the lake District over the last *c.* 150 years. Whilst the Haweswater, Sleddale and Kent catchments showed the lowest percentage of adjustment over all time periods in the Lake District study region, boundary, width, bend and bar adjustments are still present in these catchments and there are local zones of sediment erosion, deposition and planform adjustment indicating that these are active systems, but less active than the other catchments studied.

In summary, at the regional scale the USC provides a useful framework for understanding the regional (multiple catchment) patterns and controls of 2D adjustment and stability (Fig. 6.32). The USC structure is determined by the geological and glacial legacies which determine topographic confinement and sediment supply. Valley bottom width is therefore an important variable influencing the spatial pattern of planform adjustment and stability at the regional scale. However, the analysis highlights that there is catchment to catchment variability in the spatial pattern of adjustment and stability and this is attributed to local reach scale controls (e.g. anthropogenic activity such as mining or river channelization).

6.7.2 Temporal pattern of planform adjustment and stability

The temporal pattern of planform adjustment and stability is often linked to flood frequency and magnitude (Wolman and Miller, 1960; Anderson and Calver, 1980; Milne, 1982; McEwen, 1989; Milan, 2012; Pattison and Lane, 2012; Heritage and Entwistle, 2019), and anthropogenic activity (Gilvear and Winterbottom, 1992; Surian and Rinaldi, 2003; Fryirs et al., 2009). In Chapter 4, planform adjustment and sediment discontinuity is observed along St John's Beck in response to the extreme Storm Desmond rainfall event. Geomorphic impacts of flood events have been observed along St John's Beck after the 1995, 2005 and 2009 floods (Joyce et al., 2018). However, in the 150 year catchment scale analysis of planform adjustments, St John's Beck exhibited relative 2D channel stability (Fig. 6.21). This is because evidence of flood events can be quickly cleared and therefore are not captured in the snapshot of river planform identified in air photographs and historic maps.

In the Wasdale catchment study (Chapter 5) the analysis of the longer-term patterns of adjustment and links to flood-rich periods and anthropogenic activity was also challenging because (i) of the availability and resolution of historical data (maps of river planform and records of channel modification/anthropogenic activity); (ii) adjustments can occur in response to endogenic processes or in response to exogenic controls and river response can be similar in both instances (equifinality), (iii) adjustments can be short-lived (intransient), instantaneous, lagged, or progressive and therefore the direct cause and impact may not be identifiable from available resources (Schumm and Lichty, 1965; Lewin, 1977; Chappell, 1983; Donovan et al., 2019) and (v) local orographic controls influence the spatial pattern of rainfall and therefore catchment response can vary spatially in flood-rich periods (Fig. 6.40).

A similar pattern emerges across the Lake District study region, where over all epochs studied, the total length of adjustment and stability was relatively consistent, despite the occurrence of five flood-rich periods and evidence of anthropogenic channel modification influencing sediment continuity (Fig. 6.42). Therefore, the analysis of historic maps and air photographs provide a 'snapshot' observation of planform stability over the last *c.* 150 years, but temporal correlations with anthropogenic activity (e.g. river management) and regional flood events are difficult to confirm at the regional scale.

Figure 6.42 summarises the mean adjustment length, flood-rich periods, climate trends and anthropogenic activity over the last *c.* 150 years in the Lake District upland region. Human activities have been altering river planform and sediment continuity over the last millennium indirectly through changes in land use and directly via channel modifications in the Lake District study region (Pennington, 1991; Edwards and Whittington, 2001; Chiverrell, 2006; James and Lecce, 2013; LDNPA, 2017). For example, in the Coniston catchment the highest percentage of total channel length mapped as adjusting was observed in the 1860s-1950s historic map comparison (11 %, Fig. 6.22) coinciding with the period after peak copper production (1860s), where anthropogenic boundary adjustments are identified (Fig. 6.34). Mining activities stopped in 1960s, therefore explaining the lower percentage of adjustment (5 %) observed in 1950s-1980 historic map comparisons in the Coniston catchment (Fig. 6.22). However, the link between planform adjustment and anthropogenic activity is not a linear relationship, river activity mapped may be lagged or progressive and reflect anthropogenic legacy effects that occurred over longer time periods >150 years (Dufour and Piégay, 2009; Piégay et al., 2020).

In summary, at the event and reach scale (St John's Beck study, Chapter 4) the impacts of flood events on planform adjustment can easily be quantified. As the temporal and spatial scale increases, for example from catchment (e.g. Wasdale study Chapter 5) to regional, multiple catchment scale (Chapter 6) over the last 150 year the correlations between flood events and planform adjustment and stability are harder to define given the resolution of the available data.

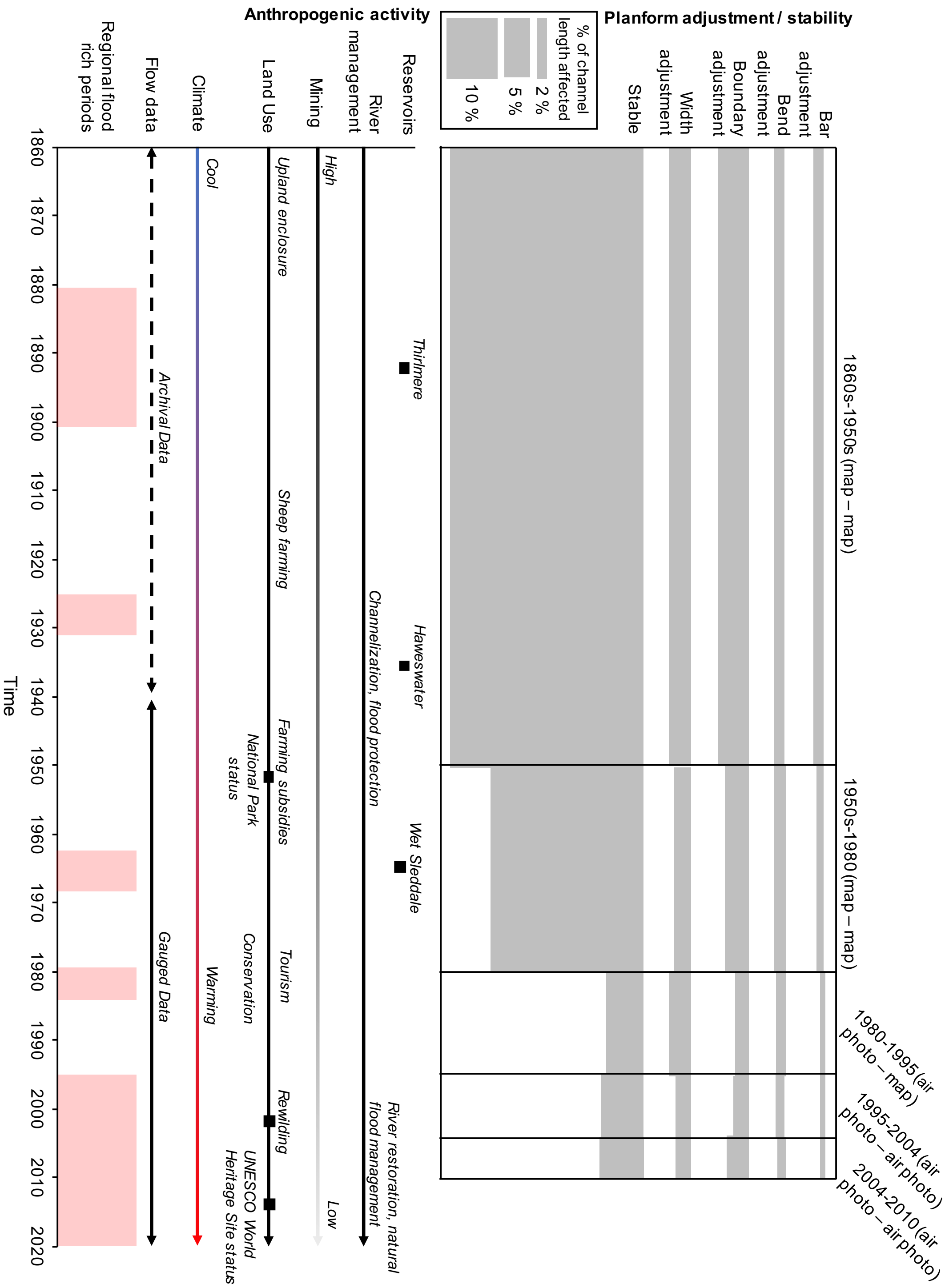


Figure 6.42. Changes in climate, flood-rich periods, anthropogenic activity and planform adjustment across the Lake District upland region over the last 150 years.

6.7.3 Chapter conclusions

The aim of this research is to quantify the spatial patterns and geomorphic variables influencing upland river planform adjustment and stability over the past *c.* 150 years at the reach, catchment and multiple catchment scale. This chapter has explored patterns of 2D planform adjustment and stability across 17 catchments in the Lake District upland region from the 1860s - 2010. The results of this chapter show:

1. *The spatial pattern of planform adjustment and stability in a catchment can be summarised using the upland sediment cascade (Fig. 6.32).* Headwater channels are topographically confined, with steep channel slopes, high specific stream powers and narrow channel widths showing relative 2D stability (Fig 6.20). In contrast, the floodplain valley transfer zone is characterised as an area of sediment discontinuity with local sedimentation zones as the channel slope and stream power decreases and valley bottom width increases creating accommodation space for sediment deposition and lateral adjustment (Figs. 6.19, 6.20). The spatial pattern of planform can deviate from the USC framework where rivers have been impacted by anthropogenic activity that may alter the quantity and rate of sediment supplied to the channel (e.g. mining activities), (Fig. 6.34), or restricts the channel from adjusting (e.g. bank reinforcements).

2. *Geological and glacial legacies in the Lake District have set the topographic conditions (confinement, U-shaped valleys, channel slope) and calibre and supply of sediment to rivers, which determine the radial drainage pattern and upland sediment cascade structure (Fig. 6.40).*

3. *Regionally, stable and adjusting reaches had statistically significant differences between the mean geomorphic characteristics: slope, valley bottom width, channel width and specific stream power (Table 6.7, Fig. 6.40).* Stable reaches had a mean channel width 6 ± 5 m, slope 0.052 ± 0.053, specific stream power 340 ± 260 W m^{-2}, and valley bottom width 110 ± 170 m. Adjustment reaches had a mean channel width 7 ± 6 m, slope 0.046 ± 0.053, specific stream power 310 ± 250 W m^{-2} and valley bottom width 120 ± 190 m. Valley bottom width and channel width have the highest number of statistical differences between the

planform adjustment types through the stream order hierarchy (Table 6.8) and were the best predictor of planform adjustment and stability. Catchment area was a poor predictor of planform adjustment at the regional scale (Table 6.6); Fig 6.38. In the Lake District region, no statistically significant differences were identified between catchment areas of stable and adjusting reaches (Table 6.6).

4. *Determining the relative importance of different endogenic and exogenic controls of planform adjustment and stability cannot be easily resolved at the regional scale (Fig. 6.40).* This research presents the first regional scale assessment of the patterns of planform adjustment over the last *c.* 150 years in the Lake District using the best available historic maps and air photograph data. It is difficult to identify the importance of the endogenic and exogenic controls because (1) planform adjustments can occur singularly, and in combination (e.g. bar and bend adjustments), (Fig 6.39) therefore making it difficult to define a singular set of geomorphic characteristics for the adjustment categories. (2) Planform adjustments occur in response to multiple endogenic and exogenic interacting, spatially (e.g. anthropogenic activity) and temporally variables (e.g. floods). (3) The identification of planform adjustment and stability controls is dependent on the availability and resolution of data relating to river planform (e.g. historic maps), flow data (gauges present) and anthropogenic activity records (land use activities and channel modifications).

5. *The regional temporal analysis allows the identification of catchments of persistent adjustment and stability (Figs. 6.16, 6.21).* Over the full period of analysis (1860s – 2010) the highest percentage of channels mapped as adjusting was recorded in the Ennerdale (37 %) and Wasdale (32 %) catchments. In contrast, catchments of persistent stability were Sleddale (10 %) and Kent (10 %).

6. *River management is concentrated in high order channels in the floodplain valley transfer zone (Figs. 6.14, 6.15).* The mean percentage of channel length mapped as managed in second order channels is: 5 ± 18 %, in third order channels 21 ± 32 %, in fourth order channels 73 ± 32 %, in fifth order channels 92 ± 23 %, and in sixth order channels is 100 % in the Lake District study region.

7. *There was a statistically significant difference in the length of planform adjustment and stability in managed and natural channels (Fig. 6.27).* In managed channels the stable reaches were shortest (mean length 7.3 ± 16.5 %) compared to in natural reaches (mean length 12 ± 25 %). Boundary adjustments were longest in managed reaches (mean length 8 ± 12 %) compared to stable reaches (4.3 ± 5.6 %).

8. *River management causes reach scale variability in the patterns of planform adjustment and stability (Figs. 6.34, 6.37).* For example, mining activities have contributed to excessive sediment loads and planform widening in the Coniston catchment causing deviations from the natural stream order patterns (Fig. 6.34).

9. *At the reach and event scale the impact of floods on planform adjustment and stability can be identified. However, with increasing spatial and temporal scale these correlations are harder to define (Figs. 6.42).* The St John's Beck study (Chapter 4) quantified the impact of the extreme Storm Desmond (December 2015) flood event on planform adjustment. However, with increasing scale identifying the impact of regional flood events on river planform stability is challenging due to the available data (e.g. timing of historic maps, flow gauges, rainfall records) and variability in local catchment response.

Chapter 7

Summary: reach, catchment and multiple catchment scale patterns and controls of river planform adjustment

7.1 Chapter summary

The aim of this research was to quantify the spatial patterns and key geomorphic variables of upland river planform adjustment and stability over the past 150 years, at the reach, catchment and multiple catchment (regional) scale. Three main research questions (RQs) were outlined (Chapter 1) to address this aim:

RQ1. How do river planform adjustments vary spatially across multiple catchments in a region over the last 150 years?

RQ2. What are the dominant exogenic and endogenic variables influencing the spatial distribution of river planform adjustments, and is this pattern catchment specific, or similar across multiple catchments in a region?

RQ3. What is the influence of low frequency, high magnitude flood events on river planform at the reach, catchment and multiple catchment scale over the last 150 years?

This concluding chapter summarises the key findings of this thesis in relation to the research questions outlined in Chapter 1, and makes links between the reach, catchment and multiple catchment scale findings (Section 7.2). Section 7.3 discusses the implication of the research for river management and restoration activities. The chapter concludes (Section 7.4) with a discussion of prospective future research based on the findings of this thesis.

7.2 Summary of research findings

7.2.1 RQ1: How do river planform adjustments vary spatially across multiple catchments in a region over the last 150 years?

This research has provided the first comprehensive multiple catchment scale assessment of the patterns and controls of river planform adjustment over the past *c.* 150 years in the Lake District (1250 km^2) upland region, UK. The spatial patterns of planform adjustment and stability has been assessed on 270 individual rivers and streams across 17 catchments in the Lake District over six time periods form 1860s – 2010. Across the 17 catchments studied, 21 % (128 km) of channels studied were adjusting over the last 150 years (Figs. 6.16, 6.21, 6.41).

Previous research has stated that upland regions are geomorphically active (Hooke and Redmond, 1989a; Wishart, 2004; Johnson and Warburton, 2002; Warburton, 2010). For example, Hooke and Redmond (1989a) reported that 35 % of UK uplands showed some form of planform adjustment from 1870s – 1950s. This research challenges this assumption that UK upland are dynamic, as 79 % of rivers studied in the Lake District upland region showed relative 2D lateral planform stability over 150 years. Therefore, this research implies there is a relative balance in the sediment hydrodynamics in large parts of the region during this period.

The Upland Sediment Cascade (USC) provides an important framework for interpreting catchment scale patterns of planform adjustment and stability observed across the Lake District upland region (Fig 6.32). Headwater channels in the production zone of the USC (e.g. second order channels) were characterised by steep channel slopes and high specific stream power values and they were topographically confined in the Lake District (Figs.

6.5, 6.7, 6.9). Bar adjustments were the most frequent forms of adjustment and accounted for 85 % of total number of adjustments in second order headwater channels. Therefore, second order channels displayed relative lateral stability indicating the potential for a high degree of sediment continuity in this zone.

In contrast, the floodplain valley transfer zone represents an active sediment supply, transfer and depositional zone, evidenced by the highest frequency of boundary, bar, width and bend adjustments (Figs. 6.19, 6.20). This is attributed to the changing geomorphic characteristics downstream as channel slope, specific stream power decrease, valley bottom width and channel width increase creating space for lateral planform adjustment and sediment deposition in this zone. However, there was variability in adjustment and stability through the USC at the reach and catchment scale, attributed to local reach scale anthropogenic activities (e.g. mining and channel management (Figs 6.34, 6.35)).

Over time, the total length of channel mapped as adjusting or stable varied spatially across the 17 catchments in the Lake District study region (Fig. 6.21). For example, between 1860s – 2010 the highest percentage of channel length mapped as adjusting were observed in the Ennerdale (37 %), Wasdale (32 %) and Calder (29 %) catchments located in the west of the Lake District (Fig. 6.41). In contrast, catchments that showed persistent stability and had the shortest percentage of channel length mapped as adjusting between 1860s – 2010 were the Kent (10 %), Sleddale (10 %) and Haweswater (11 %), (Fig 6.41). The spatial differences in planform adjustment and stability between the 17 catchments studied is attributed to variability in the geomorphic variables (slope, channel width, valley bottom width and anthropogenic activity). Adjusting catchments were characterised by a high sediment supply, large valley bottom widths providing accommodation space for adjustment and had a relatively low percentage of the channel modified by anthropogenic activity (Figs. 6.36, 6.40). In contrast, stable planforms were observed in areas influenced by a high percentage of the river channel length mapped as modified, or in areas where channels were confined and there were high specific stream powers (Figs. 6.36, 6.40). Despite the variability in the patterns and controls of planform adjustment and stability at the reach and catchment scale, the USC provides a useful general framework for conceptualising sediment continuity and the potential for planform adjustment in upland regions (Fig. 6.32).

7.2.2 RQ2: What are the dominant exogenic and endogenic variables influencing the spatial distribution of river planform adjustments, and is this pattern catchment specific, or similar across multiple catchments in a region?

Two-dimensional planform adjustments over the last 150 years reflect the legacy of exogenic factors influencing endogenic processes: discharge, stream power and sediment continuity across a catchment. A benefit of the combined, reach, catchment and multiple catchment (regional) scale approach adopted in this thesis allowed the range of exogenic controls and their influence on endogenic processes to be investigated spatially (Fig. 6.40). In this thesis, the exogenic controls: flood events (climate), anthropogenic activity, land cover, geology, and topography were considered as factors influencing endogenic processes stream power, sediment transport, erosion and deposition and therefore planform adjustment at the regional scale.

Geology and glacial processes over the last millennium set the topography, radial drainage network, availability and caliber of sediment in the Lake District upland region, which partly controls the structure of the USC and potential for planform adjustment. There were statistically significant differences between the geomorphic characteristics of stable and adjusting reaches in the Lake District study region. Stable reaches (n = 13377) had a mean channel width 6 ± 5 m, slope 0.052 ± 0.053, specific stream power 340 ± 260 W m^{-2}, and valley bottom width 110 ± 170 m. Adjustment reaches (n = 16455) had a mean channel width 7 ± 6 m, slope 0.046 ± 0.053, specific stream power 310 ± 250 W m^{-2} and valley bottom width 120 ± 190 m (Table 6.7). Valley bottom width (confinement) was found to be an important variable for determining differences between adjustment categories (in particular the occurrence of boundary adjustments), (Tables 6.7, 6.8). In large valley bottom widths (unconfined channels) there is space for lateral planform adjustment and floodplain-channel interactions.

The research findings demonstrate that planform adjustment is ultimately governed by regional geology and glacial legacies which determine geomorphic characteristics: valley bottom widths, channel slope and sediment supply, but rivers are subject to local reach scale influences (e.g. anthropogenic activity). At the reach scale, anthropogenic activity is a dominant control influencing planform adjustment and stability (Fig. 6.21). For example, anthropogenic activity can cause planform adjustment (Figs 6.34, 6.37), can modify the river to restrict adjustment (Fig. 6.35), and can alter the sediment regime, therefore influencing the type and rate of planform adjustment (Fig. 6.34). Therefore, it is important to understand both reach, catchment and regional scale characteristics can influence the patterns of river planform adjustment and stability observed over the last 150 years.

However, determining the relative importance of different endogenic and exogenic controls of planform adjustment and stability cannot easily be resolved at the regional scale. This is because: (i) planform adjustments occur in response to multiple exogenic controls and endogenic processes interacting, spatially (e.g. anthropogenic activity) and temporally (e.g. floods), therefore making it difficult to assign a singular set of geomorphic characteristics to a planform adjustment type, a case of equifinality. (ii) It is difficult to isolate the geomorphic variables of individual planform adjustment categories because planform adjustments can occur in combination (e.g. bar and bend adjustments), (Fig. 6.39). (iii) The identification of planform adjustment and stability controls is dependent on the availability and resolution of data providing a snapshot of river planform, historic records of flood events and anthropogenic activity. Despite these limitations this research presents the first comprehensive assessment of the range of exogenic controls and their influence on endogenic processes on river planform adjustments across multiple catchments in an upland region.

7.2.3 RQ3: What is the influence of low frequency, high magnitude flood events on river planform at the reach, catchment and multiple catchment scale over the last 150 years?

The temporal pattern of river planform adjustments in many upland catchments has been linked to the incidence and severity of major floods (Wolman and Miller, 1960; Anderson and Calver, 1980; Milne, 1982; McEwen, 1989; Rumsby and Macklin, 1994; McEwen, 1994; Werritty and Hoey, 2004; Wishart, 2004). Chapter 4 demonstrated the impacts of the extreme storm Desmond flood event on sediment continuity and planform adjustment at the reach scale along St John's Beck. During the December 2015 flood 6500 ± 710 t of sediment was eroded or scoured from the river floodplains, banks and 6300 ± 570 t of sediment was deposited in the channel or on the surrounding floodplains. Less than 6 % of sediment eroded during the flood event was transported out of the 8 km channel. Results indicate that, rather than upland floodplain valleys functioning as effective transfer reaches, they instead comprise significant storage zones in the USC that capture coarse flood sediments and disrupt sediment continuity downstream.

However, catchment analysis of planform adjustment over the past 150 years (Chapter 6) indicated relative 2D channel planform stability on St John's Beck despite five flood-rich periods identified over the last 150 years (Fig. 6.21). This is not surprising given the approximate sediment balance observed during the storm Desmond flood and because evidence from flood events is often quickly cleared. The St John's Beck study (Chapter 4) therefore shows that the impact of flood events on sediment continuity and planform adjustment can be readily quantified at the reach scale. However, with increasing spatial and temporal scale identifying the impact of flood events on river planform stability at the catchment and regional scale is harder to quantify (Fig. 6.42).

This research demonstrates sediment continuity is spatially and temporally variable. At the multiple catchment (regional scale) over the last 150 years there was relative lateral planform stability (79 % stable). Therefore, whilst high magnitude flood events disrupt sediment continuity and are visible at the event and reach scale, there is relative sediment continuity over the last 150 years in the Lake District upland region.

Over the last 150 years five flood-rich periods were identified in the Lake District upland region using archival records and 19 flow gauges, and were linked to patterns of planform adjustment (Figs. 5.13, 6.42). However, quantifying the impact of regional flood events on planform and adjustment at the regional scale was challenging because: (i) planform adjustments can be triggered by multiple collective exogenic controls, (ii) planform response to flood events can be short-lived, instantaneous, lagged or progressive and therefore may not be captured in the available records, (iii) the flood may not have been of sufficient magnitude to cause significant adjustment, (iv) anthropogenic activity may have restricted planform adjustment or cleared evidence of the event, (v) catchments may be influenced by orographic rainfall controls and therefore flood events may vary significantly between catchments, but due to limited number of flow gauges means this is difficult to quantify; and vi) the analysis of planform adjustment is dependent on available evidence from historic maps and air photographs that represents a series of 'snapshots' in time that may or may not correspond to a period of recent flood activity and channel change. Consequently, planform adjustment in response to low frequency, high magnitude flood events are readily identified at the reach and event scale, but the influence of flood events on adjustment at the catchment and regional scale over the past 150 years represents an area for further research development.

7.3 Implications of the research findings for river management and restoration

The spatial and temporal analysis of river planform adjustment and stability represents an important step for understanding historic and current river behavior and predicting locations of future adjustment or stability. This information can be helpful in identifying: i) areas susceptible to future adjustment, ii) relatively 'natural' catchments that can provide a template or reference condition for river restoration, and iii) reaches or catchments for river management or restoration opportunities.

The temporal analysis of planform adjustment and stability highlighted catchments of persistent adjustment and stability in the Lake District upland region over the last 150 years (Fig. 6.21, 6.41) these catchments are likely to be actively adjusting catchments in the future. Catchments of persistent adjustment over all time periods were Ennerdale, Wasdale and Calder, these catchments had less than 20 % of the river channel length categorised as managed (Fig. 6.36). Therefore, these catchments are close to 'natural' and therefore can provide a template for river restoration in catchments that have a high percentage of channels mapped as managed, such as in the Bassenthwaite catchment (Figs. 6.14, 6.35).

Traditional river management has aimed to restrict planform adjustment to maintain stability (e.g. channelization) at the reach scale in high order channels in the upper floodplain transfer zone (Figs. 6.14, 6.15, 6.35). For example, the mean percentage of channel length mapped as managed in third order channels 21 ± 32 %, in fourth order channels 73 ± 32 %, in fifth order channels 92 ± 23 %, and in sixth order channels was 100 % in the Lake District study region. In natural systems, the upper valley floodplain transfer zone is an active zone of sediment erosion, transfer and deposition and therefore planform adjustment (Fig. 6.32). Hence, instead of focusing management on adjusting reaches in the upper floodplain valley zone to create stability the following question should be asked: why do channels in the upper floodplain valley transfer zone of the USC show persistent stability? Reaches showing relative planform stability in the upper floodplain valley zone could indicate managed reaches and present an opportunity for reach scale restoration to allow natural processes of sediment erosion, transfer and deposition. For example, St John's Beck (Chapter 4) is a channelized river, in the upper floodplain valley transfer zone, and displayed relative planform stability over the last 150 years (Fig. 6.21). However, during the extreme Storm Desmond flood event (Chapter 4) significant river bank erosion and deposition was observed in artificially confined sections and the system adjusted to a more natural planform: a natural 're-wilding' process (Fig. 4.5). The system was subsequently modified and embankments were reinstated (Fig. 4.10) after the flood event. To restore natural process-form relationships would involve removing the embankments enabling the channel to naturally interact with the floodplains and erode a more sinuous planform. This research therefore can be useful for identifying reaches for management priority.

The findings of this research can be used to identify both reaches and catchments for management or restoration (e.g. Figs. 6.16, 6.21, 6.41). Catchment based management such as natural flood management schemes, (e.g. flood retention storage areas, logjams, increasing channel floodplain connectivity), will influence the supply of sediment and sediment storage zones (e.g. local storage of sediment behind logjams). The USC of a restored river system will therefore have multiple local sediment stores (e.g. flood retention features, logjams).

7.4 Directions for future research

7.4.1 Extend the spatial and temporal extent of analysis

In the Lake District upland study region assessments of planform adjustment and stability have been guided by the available full coverage historic maps (earliest 1860s) and air photographs (latest used 2010). The extreme Storm Desmond flood event (December 2015) was the largest flood event in the >558 year flood record determined from lake sediment archives (Chiverrell et al., 2019) and caused significant geomorphic work which was recorded at the reach scale through field investigations along St John's Beck (Chapter 4). To further investigate the impacts of the Storm Desmond flood on sediment continuity and planform adjustment at the catchment and regional scale throughout the USC, recent full coverage air photographs could be used to map planform adjustment and stability (e.g. 2019 Google Earth Satellite imagery). This will allow the spatial patterns of adjustments observed across the study region to be identified and placed in the context of this recent extreme flood event. This will help to identify the influence of low frequency, high magnitude flood events at the catchment and multiple catchment scale (RQ3).

The methodology developed has been applied and tested on the Lake District upland region, north-west England. However, the methodology developed could be applied to other larger or smaller upland areas (e.g. Scottish uplands) to view the patterns and controls of river planform adjustment over the past *c.* 150 years. Ordnance Survey, 1860s historic maps are readily available for the UK and remote sensing technologies now allow widespread rapid acquisition of large scale air photography. Therefore, there is potential to extend the analysis to other upland regions using available topographic data and make multiple regional comparisons of planform adjustment and stability.

7.4.2 Investigate the influence of high magnitude, low frequency flood events on sediment continuity and planform adjustment in greater detail at the catchment and regional scale

In this thesis, the influence of high magnitude, low frequency flood events on planform stability was identified at the reach scale (Chapter 4). However, linking flood-rich periods to planform adjustment and stability at the catchment and regional scale remains a challenge. This is because of the lack of flow gauges in the upland region, 19 gauges were present in the study region, but not all of the catchments studied had a flow gauge (e.g. Wasdale, Ennerdale). Flow gauges were often positioned on high order channels, downstream of lakes or reservoirs in the upper floodplain valley transfer zone of the USC.

There is spatial heterogeneity in rainfall across the Lake District related to orographic controls and rain shadow effects (Fig. 6.40), (Jones and Conway, 1997; Barker et al., 2004). Therefore, it is expected that there will be spatially variability in flood events (Johnson and Warburton, 2002) and impacts on planform adjustment across the region. To better constrain the flood record in the region, dating of flood deposits (such as boulders, berms) using lichenometry could be completed. This will provide an indication of localised flood events in headwaters of the USC. Sediment cores from lakes (Chiverrell et al., 2019) or floodplains (Fuller et al., 2019) also provide the opportunity for dating historical flood events across the upland region. If this is done across multiple catchments across the upland region in the production and transfer zone of the USC, this will allow the influence of localised floods on planform adjustment to be distinguished from catchment and regional scale flood events.

7.4.3 Produce a multiple catchment sediment budget for the past 150 years

Sediment continuity has been inferred by assessing patterns of planform adjustment and stability over the past 150 years in the Lake District study region. In Chapter 4 a sediment budget was produced for St John's Beck, in the upper floodplain transfer zone of the USC. To extend this analysis, sediment budgets can be produced in the headwater production zone via field survey or patterns of planform adjustment (e.g. changes in channel area, bar area) can be extracted from the GIS data and converted into areas. Using local measurements of sediment depths and bulk densities (e.g. using the field data collected in Chapter 4 on St John's Beck), sediment mass transfer over the historical time period in the Lake District upland region can be quantified. Sediment budgets can then be compared in the headwater production zone and valley floodplain transfer zone to understand sediment continuity along the full upland sediment cascade.

7.4.4 Investigate the probabilities of future planform adjustment

This research has quantified the spatial patterns and geomorphic variables of river planform adjustments over 150 years in the Lake District and analysed the data using correlative and linear approaches (Chapter 5 and 6). The data collected within this research could be used to identify the probability of planform adjustment occurrence using the geomorphic characteristics as explanatory variables. This could be further investigated using multivariate logistic regression models (Downs, 1994; 1995), principle component analysis (David et al., 2016) or machine learning (Piégay et al., 2020). Further analysis will quantify the probability of planform adjustment occurrence; this would allow management and restoration decisions to be made with a quantitative evidence base.

Appendix A

Published paper:

Joyce, H.M., Hardy, R.J., Warburton, J. and Large, A.R., (2018). Sediment continuity through the upland sediment cascade: geomorphic response of an upland river to an extreme flood event. Geomorphology, 317, pp. 45-61.

Geomorphology 317 (2018) 45–61

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Sediment continuity through the upland sediment cascade: geomorphic response of an upland river to an extreme flood event

Hannah M. Joyce [a,*], Richard J. Hardy [a], Jeff Warburton [a], Andrew R.G. Large [b]

[a] Department of Geography, Durham University, Lower Mountjoy, South Road, Durham DH1 3LE, UK
[b] School of Geography, Politics and Sociology, Newcastle University, Newcastle Upon Tyne, NE1 7RU, UK

ARTICLE INFO

Article history:
Received 15 February 2018
Received in revised form 29 April 2018
Accepted 1 May 2018
Available online 1 June 2018

Keywords:
Sediment continuity
Extreme floods
Fluvial sediment budgets
Upland sediment cascade
Floodplain sediment storage

ABSTRACT

Hillslope erosion and accelerated lake sedimentation are often reported as the source and main stores of sediment in the upland sediment cascade during extreme flood events. While upland valley floodplain systems in the transfer zone have the potential to influence sediment continuity during extreme events, their geomorphic response is rarely quantified. This paper quantifies the sediment continuity through a regulated upland valley fluvial system (St John's Beck, Cumbria, UK) in response to the extreme Storm Desmond (4–6 December 2015) flood event. A sediment budget framework is used to quantify geomorphic response and evaluate sediment transport during the event. Field measurements show 6500 ± 710 t of sediment was eroded or scoured from the river floodplains, banks and bed during the event, with 6300 ± 570 t of sediment deposited in the channel or on the surrounding floodplains. <6% of sediment eroded during the flood event was transported out of the 8 km channel. Floodplain sediment storage was seen to be restricted to areas of overbank flow where the channel was unconfined. Results indicate that, rather than upland floodplain valleys functioning as effective transfer reaches, they instead comprise significant storage zones that capture coarse flood sediments and disrupt sediment continuity downstream.

1. Introduction

Upland rivers are active geomorphic systems that generate some of the highest annual global sediment yields (Milliman and Syvitski, 1992). The steep channel gradients, high runoff and dynamic geomorphic processes result in high rates of sediment production, transfer, deposition and geomorphic change (Johnson and Warburton, 2002; Warburton, 2010). These processes are greatest during high magnitude, low frequency, extreme flood events when sediment yields can increase by orders of magnitude, even when averaged over centennial to millennial timescales (Korup, 2012; Wicherski et al., 2017). The geomorphic impacts of these extreme events such as riverbed and bank erosion (Prosser et al., 2000; Milan, 2012; Thompson and Croke, 2013), channel widening (Krapesch et al., 2011), overbank sediment deposition (Williams and Costa, 1988; Knox, 2006), floodplain scour (Magilligan, 1992) and the destruction of protection structures (Langhammer, 2010) can have significant impacts on upland river valleys and surrounding society and infrastructure (Davies and Korup, 2010). Many of these upland systems have been anthropogenically modified to minimise the geomorphic impacts of 1 in 100 yr flood events (Hey and Winterbottom, 1990; Gergel et al., 2002), but under extreme flows managed river corridors can be reactivated.

Previous research has focused on understanding the controls of such geomorphic change during extreme events to help better predict and manage the impacts. For example, studies have explored the potential for geomorphic work through magnitude-frequency relationships (Wolman and Gerson, 1978), hydraulic forces (i.e., discharge, shear stress, stream power (Magilligan, 1992; Thompson and Croke, 2013)), catchment characteristics such as valley confinement (Righini et al., 2017), the role of engineered structures (Langhammer, 2010) and anthropogenic modifications (Lewin, 2013). However, only a few studies (Trimble, 2010; Warburton, 2010; Warburton et al., 2016) have investigated the geomorphic impacts of extreme events in terms of sediment continuity of the upland catchment sediment cascade (USC). Here, sediment continuity is defined as the physical transfer or exchange of sediment from one part of the fluvial system to another, and represents the conservation of mass between sediment inputs, stores and outputs. Sediment continuity is therefore distinct from the concept of sediment connectivity (Hooke, 2003; Bracken et al., 2015) as it describes the pathways for sediment transfer by quantifying the physical movement and storage of sediment mass.

The USC describes the supply, transfer and storage of catchment sediment from source to sink (Chorley and Kennedy, 1971; Slaymaker, 1991; Burt and Allison, 2010). Fig. 1 provides a framework for the USC

* Corresponding author.
E-mail address: hannah.joyce@durham.ac.uk (H.M. Joyce).

https://doi.org/10.1016/j.geomorph.2018.05.002

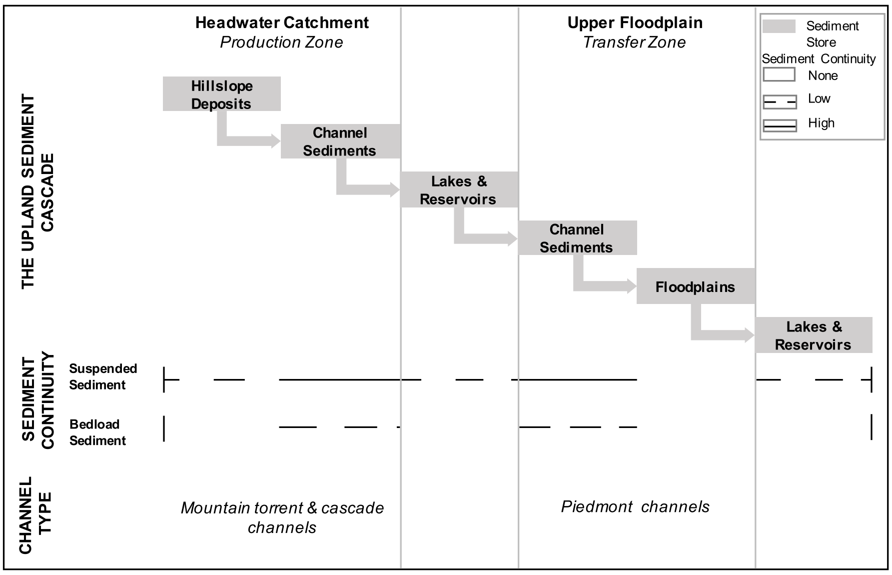


Fig. 1. The upland sediment cascade (USC) framework displaying sediment stores and the relative sediment continuity through each store during non-flood conditions. The USC framework is modified from Schumm's (1977) Simple Sediment Cascade model.

displaying the main sediment stores that are often characterised in upland sediment budget studies (Reid and Dunne, 1996; Fuller et al., 2002; Brewer and Passmore, 2002). The USC is adapted from Schumm's (1977) simple sediment cascade (SSC) model that divides the fluvial system into the production zone, transfer zone and deposition zone. In many upland regions however, the SSC is modified due to the presence of water bodies such as lakes, reservoirs or impoundments, which restrict sediment continuity between zones (Foster, 2010). Many of these water bodies (>40%) are the product of previous glacial activity that has scoured over-deepened basins (Herdendorf, 1982; Foster, 2010; McDougall and Evans, 2015). These basins occur both towards headwaters, between catchment production and transfer zones, as well as in lowland reaches where they form major long term depositional sites (Petts, 1979; Williams and Wolman, 1984; Kondolf, 1997). The movement of coarse sediment in and between the zones of the USC has been compared to a 'jerky conveyor belt' (Ferguson, 1981; Newson, 1997) where sediment is transferred and stored over a range of temporal scales. Sediment stores can fuel or buffer sediment transport rates and therefore influence sediment continuity and potential geomorphic change downstream; this is particularly relevant during less frequent higher magnitude events where sources and stores of sediment can rapidly change over a short period of time (Davies and Korup, 2010; Fryirs, 2013).

The USC production zone is characterised by mountain torrent and cascade channels that have steep channel slopes (>0.03–0.30) and surrounding hillslopes (>0.15–0.7) (Montgomery and Buffington, 1993). Here, channels are confined by the local valley topography and have no intervening floodplain; hillslopes are strongly (>80%) coupled to the channel (Lewin, 1981; Montgomery and Buffington, 1993; Harvey, 2001; Korup, 2005; Crozier, 2010). Sediment flux in this zone is dominated by suspended sediment, but during flood events bedload and coarse sediment stored on hillslopes can be mobilised, thus contributing to the total sediment load (Ashbridge, 1995). Hillslope erosion processes (mass wasting or water-driven) are the principal sources of sediment, which is deposited either on the hillslopes or in the channel (Montgomery and Buffington, 1993; Fuller et al., 2016). Previous studies have explored sediment dynamics in the USC production zone including: (i) hillslope-channel coupling relationships (Harvey, 2001, 2007; Johnson et al., 2008; Smith and Dragovich, 2008; Caine and Swanson, 2013), (ii) variability in sediment supply, transfer and deposition (Johnson and Warburton, 2006), (iii) response of these systems to extreme flood events (Johnson and Warburton, 2002) and (iv) the relative contribution of sediment sources to the channel through sediment budgeting approaches (Warburton, 2010).

In contrast, in the transfer zone (Fig. 1), sediment sources and deposits differ from those of the production zone as the channel (or piedmont channel) gradient decreases (slopes of <0.001–0.03), floodplain width increases, and the channel becomes unconfined allowing greater channel-floodplain interaction (Lewin, 1981; Church, 2002). Hillslope erosion processes are disconnected from the active channel by floodplains and therefore do not contribute directly to channel sedimentation (Lewin, 1981; Church, 2002). Instead, sediment in this zone is sourced from tributary inputs and reworked from channel bed and bank deposits. Suspended sediment dominates the low to medium flow sediment fluxes, with bedload sediment stored in the channel only mobilised at 50–60% of bankfull flow (Carling, 1988; Knighton, 1998; Fuller et al., 2002). Only during overbank flow is the largest bedload sediment entrained in quantity in this zone (Carling, 1988). Sediment continuity in the transfer zone is heavily influenced by anthropogenic modifications to the system (Fryirs et al., 2007; Lewin, 2013). The presence of upstream reservoirs or impoundments disrupt coarse sediment supply from headwaters, and influence the potential for sediment transport downstream through flow regulation (Petts and Thoms, 1986; Kondolf, 1997). Many of these systems have become "genetically modified" over time (Lewin, 2013) with channels artificially confined by flood protection structures to safeguard adjacent land, reducing channel-floodplain interactions. Consequently, sediment continuity and potential for sediment storage on the floodplains during extreme flood events is heavily modified by anthropogenic activity (Wohl, 2015).

Previous research has discussed the impacts of lakes, dams and impoundments on downstream sediment transport in the USC transfer zone (Gurnell, 1983; Kondolf, 1997; Petts and Gurnell, 2005). More recently, Sear et al. (2017) modelled the response to the 2009 and 2015 Cumbria floods on the Lower River Derwent, downstream of Bassenthwaite Lake, showing how the modified confined channel reverted to a course dictated by the wider valley morphology. However, the continuity of sediment transfer through intervening modified valley systems has only rarely been directly surveyed or evaluated in detail after extreme flood events (i.e., Johnson and Warburton, 2002; Warburton, 2010) and few studies have looked at how these systems recover following these extremes (Milan, 2012).

Understanding sediment continuity during extreme events in upland valley systems will become increasingly important for hazard management given projected increases in winter precipitation from predicted climate change (Raven et al., 2010; van Oldenborgh et al., 2015). However, extreme flood events are difficult to predict (Lisenby et al., 2018) and there are few direct measurements from these events. Consequently, their impacts have to be inferred from historical information and estimates of the quantity of sediment stored and transported are generally poorly constrained.

This paper quantifies the geomorphic response of an upland river valley system (transfer zone) to Storm Desmond, an extreme flood event that hit Cumbria, Northwest UK in December 2015. Specifically we (i) quantify the geomorphic impacts of the extreme event on the upper floodplain valley system of the USC; (ii) estimate bedload sediment transport rates during the flood; (iii) evaluate system recovery one year after the flood event and (iv) place findings within the wider context of sediment continuity through the USC. This study is the first to quantify the role of the floodplain zone in the USC in response to an extreme event and thus will enable better understanding of sediment continuity in upland regions.

2. Study site

This study focused on St John's Beck, an 8 km channelised, regulated gravel bed river downstream of Thirlmere Reservoir, Central Lake District, UK (OS National Grid Reference (NGR): NY 318203, catchment area including Thirlmere Reservoir is 53.4 km^2, effective catchment area is 12 km^2) (Fig. 2a). St John's Beck is a tributary to the River Greta that flows through the town of Keswick before discharging into Bassenthwaite Lake (area = 5.1 km^2). St John's Beck ranges in altitude from 178 m OD at the Thirlmere Reservoir outlet to 130 m OD where it joins the River Greta (Fig. 2a). St John's Beck lies in the upper floodplain transfer zone of the USC (Fig. 2b). The channel has a Strahler (1952) stream order of 3, mean channel slope of 0.005 and mean channel width of 12 m. St John's Beck lies in a previously glaciated valley (Vale of St John's) that is underlain by Ordovician Borrowdale Volcanic rocks in the north of the catchment and the Skiddaw group in the south. The land surrounding the channel is predominantly mixed woodland and pasture used for livestock grazing. St John's Beck is a Site of Special Scientific Interest and lies in the Derwent and Bassenthwaite Lake Special Area of Conservation. The river is protected to support salmon, lamprey species, otters and floating water plantain (Wallace and Atkins, 1997; Reid, 2014).

St John's Beck has a wandering planform which has been restricted laterally due to channelisation in the late nineteenth century following the impoundment of Thirlmere Reservoir (area = 3.3 km^2). The channel is confined by the natural valley topography in the upstream reaches. Floodplain valley width increases 1.8 km downstream from Thirlmere Reservoir (Fig. 2a), however the river channel has been modified and restricted from movement here (1.8–5 km downstream) through bank reinforcement and flood protection levees. Flood protection levees were built to protect farmland and a major link road from flooding. Long term flow regulation has influenced sediment transport rates in St John's Beck and as a result the system displays clear zones of aggradation. There are four first order tributaries that flow into St John's Beck. Flow and sediment are intercepted from two of these tributaries, which drain the Helvellyn mountain range and are directed to Thirlmere Reservoir (Reid, 2014; Bromley, 2015). The third and fourth first order tributaries are constrained by the presence of a road and a sediment trap and therefore are not a major source of sediment to St John's Beck.

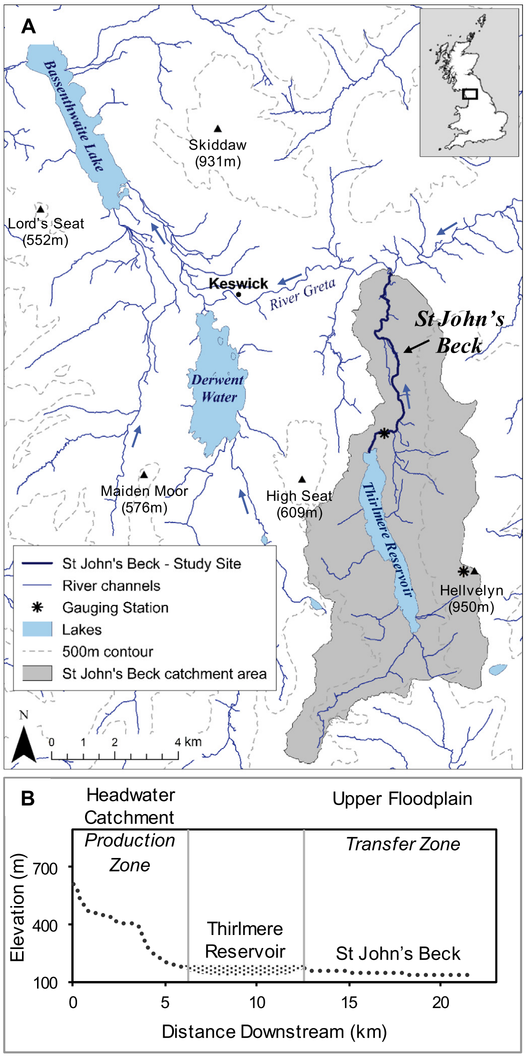


Fig. 2. (A) Location and catchment area of St John's Beck, Cumbria, UK, identifying the study reach and catchment discharge and rainfall gauging stations. Arrows indicate flow direction. (B) Long profile through the St John's Beck catchment showing the interruption of Thirlmere Reservoir on the USC.

3. The Storm Desmond flood event

Extreme flood events in the Lake District have been documented from 1690 to the present (Watkins and Whyte, 2008) (recent floods summarised in Table 1). This study describes the geomorphological impacts of the Storm Desmond (4–6 December 2015) flood event. Storm

Table 1
Recent flood events in Cumbria, UK, including the 24-h rainfall total and 24-h rainfall return period.

Date of event	Rainfall (mm) in 24-h period	Estimated 24-h rainfall return period (yr)	Reference
31 January 1995	163.5	80	Johnson and Warburton (2002)
7–8 January 2005	173	100	Roberts et al. (2009); Environment Agency (2006)
18–20 November 2009	316.4	480	Sibley (2010); Stewart et al. (2010); CEH (2015)
Storm Desmond, 4–6 December 2015	341.4	1300	CEH (2015)

Desmond, a North Atlantic storm, was associated with a mild and moist slow moving low pressure system located northwest of the UK that brought severe gales and exceptionally persistent heavy rainfall over northern UK (Met Office, 2016). Northern England experienced the wettest December on record (in a series from 1910), following the second wettest November, after 2009 (McCarthy et al., 2016). The average December rainfall doubled in northern England, with the Lake District receiving three times its average monthly rainfall (McCarthy et al., 2016). Storm Desmond produced record-breaking rainfall maximums in the UK: 341.4 mm rainfall was recorded in a 24 h period at Honister Pass (NGR NY 225134), Western Lake District, and 405 mm of rainfall was recorded in a 38 h period at Thirlmere (study catchment), central Lake District (NGR NY 313194). The storm was the largest in the 150 yr local Cumbrian rainfall series (1867–2017), and exceeded previous records set in the 2005 and 2009 Cumbrian floods. The estimated return period for the rainfall event was 1 in 1300 years (CEH, 2015) based on the FEH13 rainfall frequency model (Stewart et al., 2014). The UK climate projection change scenarios for northwest England predict winter flood events like this will occur more often in the future because of increases in rainfall intensity due to climate change (Watts et al., 2015).

3.1. Storm Desmond impacts

Storm Desmond caused widespread disruption across northern England, and in particular in upland areas in the Lake District region. The event captured national attention when extreme weather conditions prompted a full scale emergency response to extreme flooding, erosion and sediment movement by upland rivers. Over 5000 homes were flooded, access routes were destroyed (257 bridges destroyed) and key infrastructure was affected, including the erosion of the main A591 trunk road through the central Lake District. The latter was estimated to cost the local economy £1 million per day (BBC, 2016). In the production zone of the USC, saturated hillslopes and high porewater pressures triggered landslides in a number of valleys, with sediment eroded and transported through mountain torrents (Warburton et al., 2016). Geomorphic impacts in the upper floodplain system of the USC included the erosion of riverbed and banks, floodplain scour, scour around man-made structures (bridges, levees) and extensive deposition of coarse sediment across floodplains. Storm Desmond caused severe flooding and substantial geomorphic change along St John's Beck (Fig. 3).

3.2. Hydrological regime in St John's Beck

Flooding is not unusual in St John's Beck, historic accounts describe a "most dreadful storm… with such a torrent of rain, [which] changed the face of the country and did incredible damage in [St John's in the Vale]" in 1750, (Smith, 1754). This historical event has characteristics similar to that of Storm Desmond, with large boulders of sediment being transported and deposited on floodplains along the transfer zone. Long term rainfall records available for the St John's Beck Catchment (Fig. 4a, Helvellyn Birkside gauging station NGR NY 338133, ~6.3 km south of St John's Beck; Fig. 1) show Storm Desmond contributes to the greatest monthly rainfall event (1361 mm rainfall in December 2015) being five times higher than the mean December rainfall total in the 150 yr time series. The rain gauge on St John's Beck (NGR NY 313 195; Fig. 1) shows the rain that fell during December 2015 fell on previously saturated ground, following a total of 559 mm in November 2015 (Fig. 4b). These antecedent conditions comprise the second wettest November recorded at this site after the 2009 floods (Met Office, 2016). Daily rainfall totals (Fig. 4c) show the event peaked on 5 December 2015, where over a 15 min peak period, an estimated 6.8 mm of rain was recorded. Discharge records for St John's Beck (Fig. 5a) similarly show Storm Desmond was the largest magnitude event in the 82 yr flow record with an estimated peak discharge recorded during the event of 75.4 $m^3\ s^{-1}$ (Fig. 5b). Mean discharge for St John's Beck during the 82 yr record period is 0.85 $m^3\ s^{-1}$; in 2015 mean discharge was 2 $m^3\ s^{-1}$.

4. Methods

This study analyses geomorphic data collected during two field campaigns at St John's Beck. The first survey was completed after the Storm Desmond flood (April–May 2016) to capture the geomorphic impacts of this event before clean-up operations and reworking of flood sediments occurred. The second survey was conducted in June 2017 to assess short-term system recovery following the flood. All field data were digitised and analysed in a GIS in British National Grid coordinates. A 5 m resolution digital elevation model (DEM) (Digimap, 2016), pre-flood aerial imagery, 2009–2011, (from Bluesky International Limited, resolution 0.25 m) and post-flood event, May 2016, (from the Environment Agency, resolution 0.2 m) were used for validating field measurements and to assess valley topographic and local controls of the geomorphic impacts observed.

4.1. Geomorphic analysis

4.1.1. Channel geometry and bed material

A Leica Geosystems Real Time Kinetic differential GPS (RTK dGPS) 1200, was used to survey channel cross section geometry, floodplain geometry and thalweg long profile during the 2016 and 2017 surveys. Cross section sites were chosen along the 8 km river where there was a clear change in channel geomorphology identified by a walk-over reconnaissance of the catchment in 2016. A total of 22 sites for cross section surveys were chosen along St John's Beck. Cross section 1 was located near the St John's Beck gauging station (1 km downstream from Thirlmere Reservoir), so all data collected could be discussed in relation to the flow and rainfall records (Figs. 4b, c, and 5). The last cross section was located near the confluence with the River Greta (7.8 km downstream). Ten of the cross section sites were located along a 1.3 km length reach where significant riverbank erosion and overbank flood sediment deposition occurred during Storm Desmond. Survey pegs were positioned at the endpoints of each cross section in 2016 and used as control points to allow resurvey in 2017. Cross section profile RTK dGPS measurements had a mean accuracy of $\pm$0.02 m and standard deviation of 0.06 m in the 2016 survey, and a mean accuracy of $\pm$ 0.03 m and standard deviation of 0.03 m in the 2017 survey. Bankfull channel cross-sectional area was calculated at each cross section and changes in channel bankfull capacity ($m^2\ yr^{-1}$) were calculated by differencing the data collected over the survey periods. Thalweg long profile was surveyed using the RTK dGPS. Average profile point spacing was 8 m (mean accuracy of $\pm$0.02 m and standard deviation of 0.01 m) in the 2016 survey and 12 m (mean accuracy of $\pm$0.03 m and standard deviation of $\pm$0.01 m) in the 2017 survey.

Fig. 3. Photographs of the impacts of Storm Desmond along St John's Beck and the surrounding floodplains. (A–B) Flood sediments and debris (tree trunks) transported and deposited on floodplains and in the channel. (C–D) Floodplain scour. (E) Riverbank erosion. (F) Destruction of the access bridge over St John's Beck to Low Bridge End Farm (bridge approximately 3.5 m high for scale).

Channel surface bed material was measured at each cross section following the pebble count method for grain size distribution (GSD) in the 2016 and 2017 field campaigns. The b-axis of 100 particles were randomly measured (particle under tip of the toe method; Wolman, 1954) along the width of each cross section. The median diameter grain size (D_{50}) and the 90th percentile (D_{90}) were calculated and used to understand system response and sediment transfer following the event.

4.1.2. Bedload transport

Bedload sediment transport during Storm Desmond was estimated using the Bedload Assessment for Gravel-bed Streams (BAGS) software (Pitlick et al., 2009) applying a surface-based bedload transport equation (Wilcock and Crowe, 2003). The input parameters were: the GSD of the channel bed surface, cross-sectional data including floodplains, cross section averaged bed elevation slope, flow discharge in the form of a flow exceedance curve for the event, and Manning's "n" values for a clean winding channel (0.04) and short grass floodplains (0.03) estimated from Chow (1959). Sensitivity to Manning's "n" values was assessed using Chow (1959) minimum and maximum values for the channel and floodplains. Morphological change between cross sections was calculated by subtracting the downstream cross section bedload transport rate from the upstream value to identify net erosion and deposition reaches.

Historical bedload sediment transport rates were also estimated using the BAGS model (i) as an average daily transport rate for the long-term daily discharge record 1935–2015, and (ii) for the top five discharge events in the long term (15 min interval) flow record. Whilst we assume that the cross-sectional profiles and grain size distribution are the same as the post-Desmond channel, this analysis allows us to

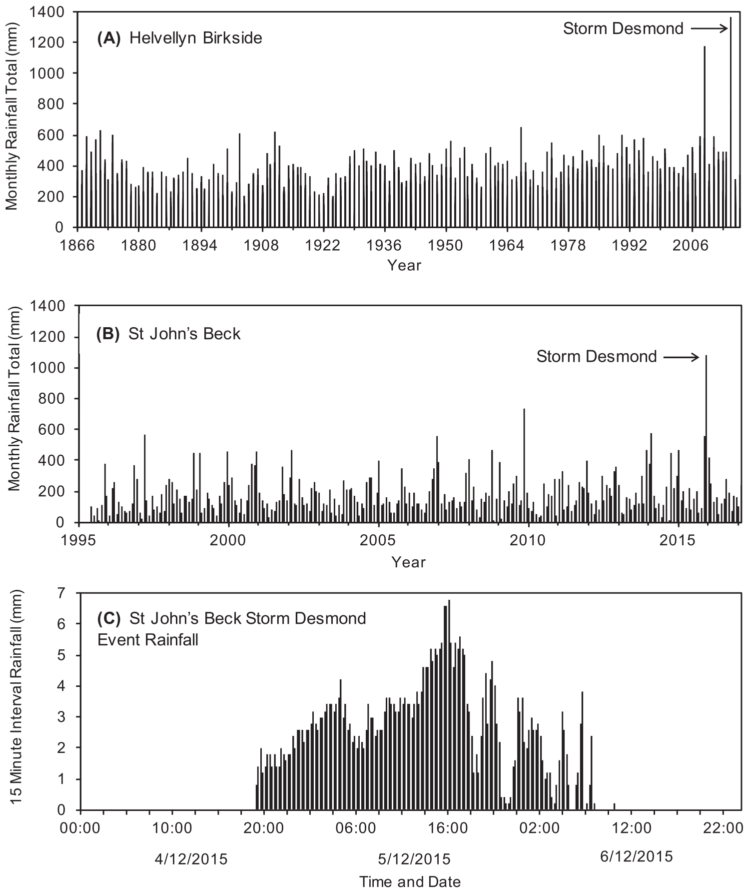


Fig. 4. Rainfall records in the St John's Beck catchment. (A) Long term (1860–2017) monthly rainfall variability in the St John's Beck catchment from the Helvellyn Birkside rain gauge (NGR NY 338133). (B) Monthly rainfall totals from the St John's Beck Environment Agency (EA) tipping bucket rain gauge (TBG) from 1995 to 2017. (C) 15 min interval rainfall record from St John's Beck EA TBG (NGR NY313 195) during the Storm Desmond flood event.

assess the importance of the Storm Desmond event on sediment transport rates in relation to the longer term system history.

4.2. Geomorphic impacts of the Storm Desmond event: sediment budget analysis

A sediment budget framework was used to quantify the geomorphic impacts of the Storm Desmond event and identify the dominant stores of sediment along St John's Beck. Sediment budgets focus on quantifying the erosion, deposition and transfer of sediment through a channel or reach over an event or time period (Reid and Dunne, 1996; Brewer and Passmore, 2002; Fuller et al., 2003). Sediment budgets represent the conservation of mass and can be summarised as (Slaymaker, 2003):

$$O_S = I_s + \Delta S_s \quad (1)$$

where O_s is the sediment output (yield) of the reach, I_s is input of sediment from dynamic sediment sources, and S_s is sediment stored on floodplains, channels etc. This framework is useful to understand local sediment continuity in response to a particular event and indicate whether a system is balanced (Reid and Dunne, 2003). The main geomorphic depositional (S_s) and erosional (I_s) features identified after Storm Desmond along St John's Beck were: floodplain sediment deposits, in-channel bars, floodplain scour, channel bed scour and riverbank erosion (Fig. 3). Floodplain scour is differentiated from bank erosion as it is associated with the stripping of the floodplain surface (vegetation) and removal of large blocks of sediment (Nanson, 1986); whereas bank erosion is defined as the removal of sediment from the bank by hydraulic action or through mass failure (Odgaard, 1987; Knighton, 1998). The volume and sediment size distribution of erosional and depositional components were measured using the RTK dGPS, and pebble count technique (Wolman, 1954) and their spatial extent was validated using the pre- and post-event aerial photographs. Channel bed scour was active during the event, however, it was not directly measured as no cross sections were monumented prior to Storm Desmond. During flood events some reaches can experience scour whilst other reaches aggrade (Reid and Dunne, 1996). The location of channel bed scour was assumed to occur where riverbank erosion or floodplain scour was observed after Storm Desmond; this was quantified using the post-event air photo and field data in GIS. The depth of

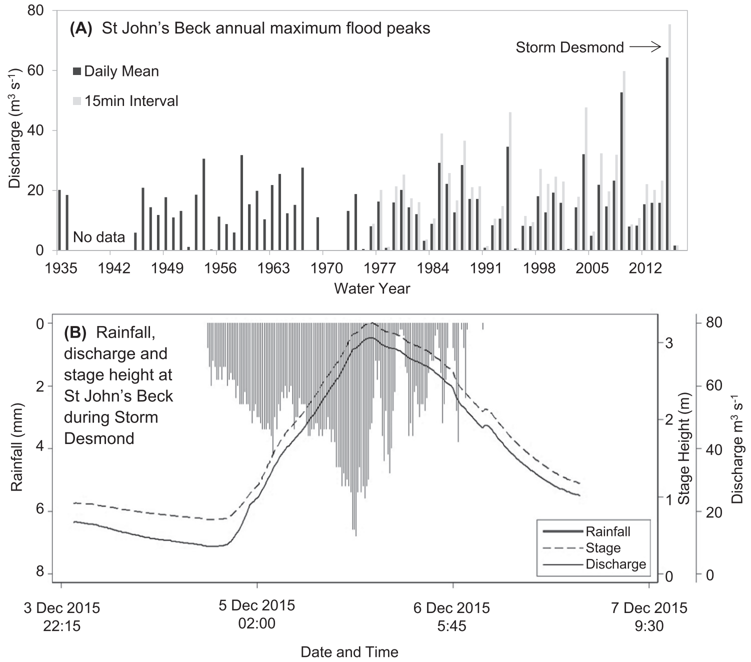


Fig. 5. Discharge records for St John's Beck gauging station. (A) Annual maximum flood peaks for St John's Beck gauging station 1935–2016 using daily mean and 15 min interval recorded flow data. (B) Estimated discharge, stage height and total rainfall during Storm Desmond.

channel bed scour was estimated according to Carling's (1987) scour-depth relation for gravel bed rivers:

$$d_s = 0.043Q^{0.27} \quad (2)$$

where d_s is depth of scour (m) and Q is the event peak discharge ($m^3\ s^{-1}$).

Volumes of sediment eroded and deposited for each geomorphic component were converted to sediment mass using local values of coarse sediment bulk density of 1860 ± 17 kg m^3 derived from the mean bulk density of 30 measured samples from the channel bed and floodplain sediment deposits.

Sediment input and output of St John's Beck during the event was estimated by converting the BAGS estimated event bedload sediment transport rates into (cross section 1, 1 km downstream) and out of St John's Beck (cross section 22, 7.8 km downstream) into the event sediment yield.

Error in sediment budgets represents a combination of survey measurements and calculations, so standard methods of error analysis are difficult to apply. Often, sediment budget error is calculated as an unmeasured residual by subtracting the erosion and deposition components (Kondolf and Matthews, 1991; Reid and Dunne, 2003). As a result, sediment budgets may balance only because errors are hidden in the residual terms (Kondolf and Matthews, 1991). To avoid misrepresentation of the sediment balance, in this study the standard error was calculated for each measurement technique for each geomorphic component. The standard errors were summed and then converted to a percentage before being converted to mass (t) for each component. For example, floodplain deposit mass error represents a combination of errors from the RTK dGPS, depth of deposit, and bulk density error measurements. The standard error from these measurements was calculated and then summed to calculate the total error percentage before being converted to the mass error (t).

4.3. Factors controlling geomorphic change

4.3.1. Lateral channel confinement ratio

Channel confinement describes the extent to which topography, such as hillslopes, river terraces and artificial structures, limit the lateral mobility of a river channel (Nagel et al., 2014). Lateral channel confinement ratio (C) was calculated as:

$$C = \frac{W_f}{W_c} \quad (3)$$

where w_f is the floodplain width and w_c is the active channel width. Floodplain width (pre- and post-Storm Desmond) is defined as the horizontal distance from the top of the channel bank to the base of the hillslope (Gellis et al., 2017); this is determined using the 2009–2011 and 2016 aerial photographs, the 5 m resolution DEM and the 2016 field data. The active channel width was measured (1) prior to Storm Desmond using the 2009–2011 aerial photographs, and (2) after Storm Desmond using the RTK dGPS channel cross section measurements and May 2016 aerial photographs. Channel and floodplain width were measured at the 22 cross section sites.

Hall et al. (2007) documented that confined channels have a confinement ratio of ≤3.8 and unconfined channels a ratio of >3.8. Channel confinement can influence the potential for sediment erosion and deposition; for example, Thompson and Croke (2013) found that in a high magnitude flood event in the Lockyer Valley, Australia, erosion was concentrated in the confined reaches, and deposition was concentrated in unconfined reaches with floodplains acting as a major store of sediment. Such behaviour may be affected by the presence of structures such as

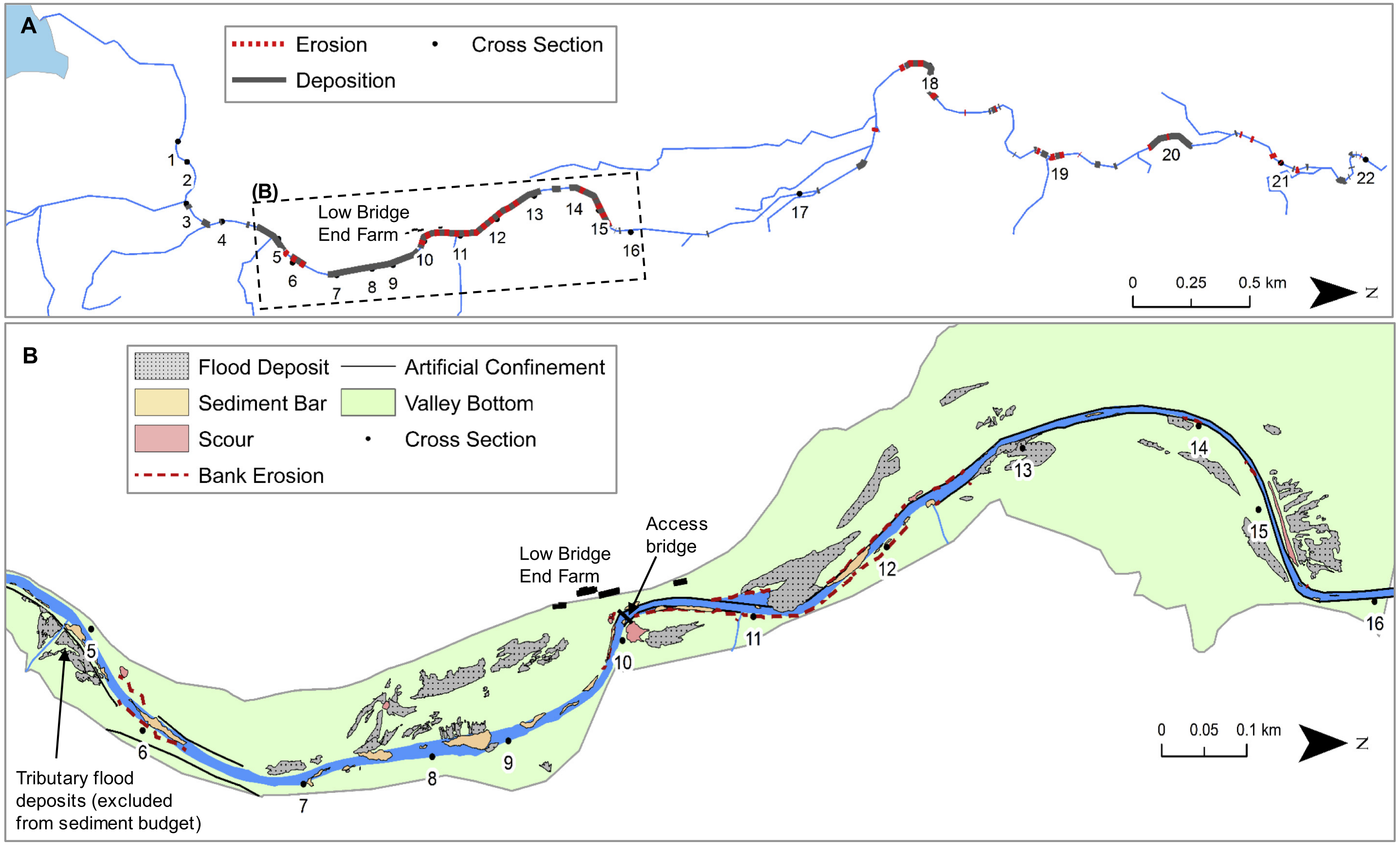


Fig. 6. Geomorphic impacts of the Storm Desmond flood event along St John's Beck, flow direction North. (A) Location of erosion and deposition impacts along St John's Beck. (B) Detailed geomorphic map showing an example reach (1.7–3.6 km downstream of Thirlmere Reservoir) with erosion and deposition impacts.

levees or roads, which are present along St John's Beck. Three types of confinement were identified along St John's Beck: (1) natural confinement, defined as the channel confinement by the natural valley bottom topography; (2) artificial confinement, where reaches of the channel have been modified through reinforced riverbanks, the presence of walls, levees, or road embankments that prevent the channel from migrating laterally; and (3) the post-Storm Desmond confinement taking into consideration the active channel width following the extreme event.

4.3.2. Stream power and shear stress

At the reach scale average shear stress, Eq. (4) (Du Boys, 1879), critical shear stress, Eq. (5) (Gordon et al., 1992), unit stream power, Eq. (6) (Bagnold, 1966) and critical unit stream power Eq. (7) (Bagnold, 1966; Williams, 1983; Petit et al., 2005) were calculated for the Storm Desmond flood to understand the potential magnitude of sediment transport rates and geomorphic impacts observed during the event using the one-dimensional uniform flow approximations:

$$\tau = \rho g d S \tag{4}$$

$$\tau_c = 0.97 D_i \tag{5}$$

$$\omega = \frac{\rho g Q S}{w} \tag{6}$$

$$\omega_c = 0.079 D_i^{1.3} \tag{7}$$

where τ is the reach averaged shear stress (N m^{-2}), ρ is the density of water (kg m^{-3}), g is the acceleration of gravity (m s^{-2}), S is channel bed slope (m m^{-1}) and d is the maximum water depth during the event (m). τ_c is the critical shear stress (N m^{-2}) and D_i is the grain size (mm). Here we use the channel D_{50} and D_{90}. ω is the unit stream power (W m^{-2}), Q corresponds to the peak discharge (m^3 s^{-1}) during Storm Desmond and w (m) is the bankfull width during the flood. ω_c is the critical unit stream power (W m^{-2}) for particle motion based on Williams' (1983) relation for gravel transport in rivers with grain sizes between 10 and 1500 mm. Calculations were applied at the cross section locations and the critical shear stress ($\tau > \tau_c$) and critical stream power ($\omega > \omega_c$) entrainment thresholds estimated to understand the potential for sediment mobility during the event. Shear stress and stream power calculations were also calculated using the June 2017 survey data (bankfull cross section profiles, grain size data, and mean daily discharge (0.085 m^3 s^{-1}) to quantify variation in shear stress and stream power during non-overbank flows.

5. Results

5.1. Geomorphic response to the storm Desmond event

Storm Desmond flood impacts along St John's Beck were concentrated in the channel and on the surrounding floodplains. The spatial distributions of both erosional and depositional impacts of Storm Desmond are shown in Fig. 6a. Generally, erosion and deposition impacts were observed in spatially similar locations, for example, where bank erosion or scour occurred overbank deposition was observed. Significant erosion and deposition impacts were observed 1.7–3.6 km downstream of Thirlmere Reservoir (Fig. 6b). Geomorphic impacts were less pronounced 3.6–8 km downstream of Thirlmere Reservoir; impacts here were often concentrated locally at meander bends (e.g., as seen at 5.2 km downstream from Thirlmere Reservoir, cross section 18). Fig. 6b shows a detailed map of the reach where significant geomorphic impacts (1.7–3.6 km downstream) were observed after Storm Desmond. Overbank floodplain deposits and channel bars measured 2.1–2.5 km downstream (between cross sections 7 to 10) occur where the channel is laterally unconfined. The channel in this reach (2.1–2.5 km downstream) was identified as aggradational (low channel capacity, channel bed nearly level with banks) in a reconnaissance survey (approach after Thorne, 1998) of the site prior to the flood. Bank erosion and scour was concentrated on the artificially-confined reach 2.5–3 km downstream (cross sections 10 to 13). Local lateral riverbank recession exceeded 12 m and caused the destruction of flood protection levees 2.7 km downstream of Thirlmere Reservoir (see cross section 11 Fig. 6b). Material eroded at cross section 11 was subsequently deposited on the floodplains downstream.

The dominant geomorphic features surveyed after the event were overbank floodplain sediment deposits. Floodplain sediment deposits located 1.8 km downstream (near cross section 5) were sourced from a tributary and not from St John's Beck. The tributary sediment did not enter St John's Beck due to a wall and sediment trapping structure, therefore, the mass of sediment measured here (300 t) is excluded from the sediment budget analysis. A total of 105 floodplain deposits were identified from St John's Beck, equating to a sediment mass of 4700 ± 300 t. Flood sediment deposits were generally composed of a single layer of sediment with a mean deposit depth 0.09 m ± a standard deviation of 0.07 m; the maximum flood deposit depth measured was 0.3 m located 2.7 km downstream of Thirlmere Reservoir. The mean grain size of sediment deposit D_{50} was 32 mm and D_{90} was 90 mm. The 10 largest clasts from the deposits had a mean grain size of 147 mm ± a standard deviation of 12.5 mm. Flood deposit grain size decreased with distance from the channel. The farthest flood deposit from the channel bank (70 m distance) had a D_{50} of 22 mm and D_{90} of 63 mm. The proximal flood deposits (2 m distance from the channel) had a mean D_{50} of 39 mm ± a 17 mm standard deviation and D_{90} of 111 mm ± a standard deviation of 35 mm.

Table 2 shows the variation in grain size between the flood sediment deposits and the channel bed sediments. Channel bed sediment D_{50} is greater than the floodplain sediment deposits, however, this pattern is reversed for sediment D_{90}. Floodplain sediment deposits are composed of material from the channel bed and from eroded features (such as artificial levees and stone walls), which generally have coarser grain sizes that could account for this variation.

Riverbank erosion and floodplain scour were the main processes accounting for a loss of sediment during Storm Desmond. Based on the field data collected, 2300 ± 270 t of sediment was eroded from the riverbanks. Floodplain scour contributed to the removal of 1300 ± 50 t of sediment during the event, 40% of sediment removed through scour was over the reach (2.2–3.6 km downstream) where significant sediment deposition was observed. Local scour of 350 ± 13 t undermined and destroyed the access bridge to Low Bridge End Farm (see cross-section 10, 2.5 km downstream of Thirlmere Reservoir, Fig. 6). The depth of channel bed scour was estimated at 0.13 m according to Carling's (1987) scour depth equation, and this equated to a mass of 2900 ± 470 t.

Fig. 7 displays the total mass of sediment eroded and deposited along St John's Beck during Storm Desmond. The greatest mass of sediment eroded and deposited occurs from 1.7 to 3.6 km downstream where the floodplain width increases from 7 to 450 m and channel

Table 2
Grain size (mm) of floodplain deposits and channel bed sediments in the May 2016 and June 2017 survey.

		Floodplain sediment deposits	Channel bed sediments (2016 survey)	Channel bed sediments (2017 survey)
d_{50}	Max	64	77	90
	Mean	32	49	53
	Std. Dev.	13	14	18
d_{90}	Max	181	90	294
	Mean	90	53	122
	Std. Dev.	37	17	35

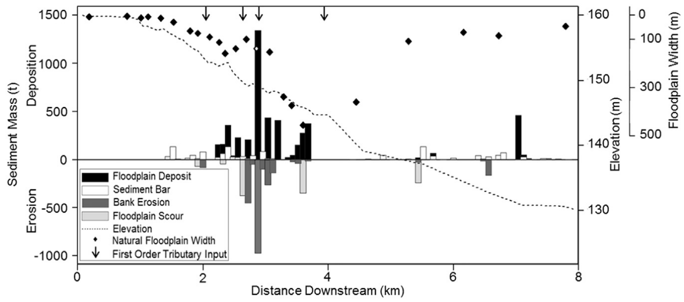


Fig. 7. Total mass (t) of sediment eroded and deposited along St John's Beck during Storm Desmond, plotted alongside the natural floodplain width and riverbed longitudinal profile.

slope steepens from 0.001 (0 to 1.7 km downstream) to 0.005 (1.7 to 3.6 km downstream). Erosion features were often balanced by sediment deposition nearby. For example, the largest mass of sediment deposited on floodplains (1340 t) correlates with the area of greatest erosion (980 t) 2.9 km downstream of Thirlmere Reservoir, where a levee was destroyed and the riverbank receded by 12 m resulting in sediment deposition over an area of 3470 m^2. Erosion and deposition impacts are less pronounced 5.2–7.8 km downstream, where the mean floodplain valley width is 77 m ± a standard deviation of 26 m, and the mean channel slope is 0.003. Erosion and deposition impacts at 5.2–7.8 km downstream were mainly concentrated on meander bends. Floodplain scour (Fig. 3c) and sediment deposition was observed on the inside of a meander bend 5.2 km downstream where overbank flows were permitted during Storm Desmond. Local bank erosion and overbank sediment deposition was observed on bends 6.8 and 7.3 km downstream.

Tree debris were observed surrounding St John's Beck following Storm Desmond. Tree debris did not cause a blockage around the access bridge to Low Bridge End Farm. However, tree debris were observed in the channel near cross section 10 (2.5 km downstream) (see Fig. 3b). The limited occurrence of woody debris in the channel inhibits the formation of log jams and only has local impacts on sedimentation.

5.2. Estimates of bedload sediment transport rate

The mean event bedload sediment transport rate for the 22 cross sections was 160 t ± a standard error of 60 t. Sediment transport rates fluctuate downstream with clear reaches of low and high sediment transfer (Fig. 8a). For example, 1.5–2 km downstream of Thirlmere Reservoir high sediment transport rates during the event (range = 220–500 t) are estimated; these are attributed to a local increase in channel slope. The maximum estimated transport rate during the event was 1200 t at 2.5 km downstream of Thirlmere Reservoir where the channel widens and local slope increases (slope 0.01) downstream of a ford, near the access bridge to Low Bridge End Farm that was destroyed during the event (Fig. 3f). The sediment input into St John's Beck during the event is estimated at 7 t (1 km downstream of Thirlmere Reservoir, cross section 1) and the sediment output (7.8 km downstream of Thirlmere reservoir, cross section 22), during the event is estimated as 370 t.

Zones of erosion and deposition along St John's Beck have been identified by differencing sediment transport rates between the surveyed cross sections (Fig. 8b). A total of 10 deposition and 11 erosion zones are defined. The zone of greatest erosion and deposition is located from 1.8 to 4 km downstream from Thirlmere Reservoir (Fig. 8b), which corresponds closely with field measurements of erosion and deposition during the event (Fig. 6).

The mean daily bedload sediment transport rate (calculated as the mean transport rate from the 22 cross sections using the 1935–2015 discharge record), is 0.05 t day^{-1} with a standard deviation of 0.09 t day^{-1}. The estimated annual bedload sediment input is estimated at 0.5 t yr^{-1} (at cross section 1) and the bedload sediment yield (at cross section 22) is 38 t yr^{-1} for St John's Beck long term discharge record. The bedload sediment output during Storm Desmond (370 t) exceeds the annual value by a factor of 9. Table 3 displays the bedload sediment transport estimates for the top five discharge events in the St John's Beck 15 min interval flow record. The Storm Desmond event produced the highest bedload sediment transport rates in the flow record, nearly double the second highest flood event in 2009.

5.3. Controlling factors that influenced geomorphic change across the reach

5.3.1. Channel confinement index

St John's Beck displays different degrees of lateral confinement downstream (Fig. 9). The natural channel confinement pattern shows that the channel becomes gradually unconfined downstream (Fig. 9). For example, in the upstream reach (0 to 1.8 km downstream of Thirlmere Reservoir) the channel is topographically confined (confinement ratios range from 0.1 to 0.6) and from 4.4 to 8 km downstream the channel is topographically unconfined (confinement ratios range

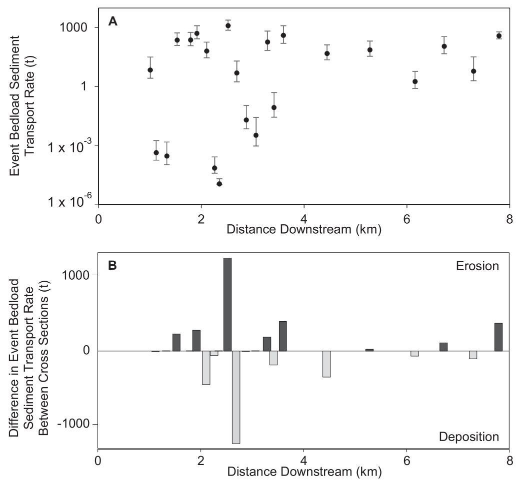


Fig. 8. Bedload sediment transport estimates along St John's Beck during Storm Desmond. (A) Storm Desmond event bedload sediment transport rates. Error bars plotted represent sensitivity to the maximum and minimum Manning's "n" values. (B) Zones of sediment erosion and deposition downstream, calculated as the difference between sediment transport rates between cross section survey locations.

Table 3
Bedload sediment transport estimates for the top five discharge events from the 15 min interval flow series data for St John's Beck. The event bedload transport rates are calculated as the mean transport rate from the 22 cross sections, and the event sediment yield is calculated at cross section 22.

			Event Bedload Sediment Transport Rate (t)			
Date of event	Estimated event peak discharge ($m^3 s^{-1}$)	Event rainfall total (mm)	Mean	Std. Dev.	Max	Event Sediment Yield
4/12/2015–6/12/2015	75.4	405.0	157	283	1229	370
17/12/2009–20/11/2009	59.8	400.0	91	166	700	210
7/01/2005–8/01/2005	47.7	180.0	30	55	188	70
31/01/1995–01/02/1995	39.0	–	25	45	151	54
21/12/1985–22/12/1985	36.6	–	21	41	142	32

from 5 to 65). The channel has been artificially confined from 1.8 to 4.4 km downstream by flood protection levees, reinforced banks and walls that restrict lateral channel movement. The mean natural floodplain width has been reduced by 90% due to the presence of artificial structures along the artificially confined reach 1.8 to 4.4 km downstream. During Storm Desmond, many of the artificially-reinforced banks and flood protection levees were scoured or eroded increasing the active channel width and allowing channel-floodplain interactions (Fig. 9). After Storm Desmond the mean confinement ratio increased from 0.95 to 17 along the artificially confined reach (1.8 to 4.4 km downstream), indicating the system reverted to a natural floodplain-channel width relationship (Fig. 9).

5.3.2. Shear stress and stream power

Shear stress and stream power are used to understand the energy expenditure for erosion and sediment entrainment during the event (Fig. 10). The shear stress values estimated for Storm Desmond are shown in Fig. 10a. The shear stress values estimated should be regarded as minimum values because they assume shear stress is the same on the channel and floodplain and the equations assume steady uniform flow, which was unlikely during the event. The mean shear stress value is 149 N m^2 with a standard deviation of 78 N m^2. The peak shear stress value (426 N m^2) was estimated 2.7 km downstream of Thirlmere Reservoir; near where the access bridge was destroyed and mass overbank coarse sediment deposition occurred. The minimum shear stress values are estimated 1.1 to 1.3 km downstream (30–60 N m^2) where local slope is 0.001. The mean shear stress value exceeded the mean critical entrainment thresholds for particle D_{50} (48 ± a standard deviation of 14 N m^2) and D_{90} (124 ± a standard deviation of 30 N m^2) (Fig. 10a), suggesting full mobility of the GSD during the event. The mean shear stress value estimated using the 2017 survey data (62 N m^2 with a standard deviation of 40 N m^2) does not exceed the threshold for mean particle D_{90} (114 N m^2) entrainment and only exceeds 60% of the cross section particle D_{50} entrainment threshold during bankfull flow conditions.

The unit stream power values estimated along St John's Beck using the peak Storm Desmond discharge value range from 25 to 354 W m^{-2}, with a mean of 230 W m^{-2} and a standard deviation of 132 W m^{-2} (Fig. 10b). The values are within the range of stream power values documented for those causing erosion during flood events and sediment transport (Baker and Costa, 1987; Magilligan, 1992; Fuller, 2008; Marchi et al., 2016). A value of 300 W m^{-2} is commonly referred to as a threshold for producing floodplain erosion (Baker and Costa, 1987; Magilligan, 1992; Fuller, 2008). Significant erosion and

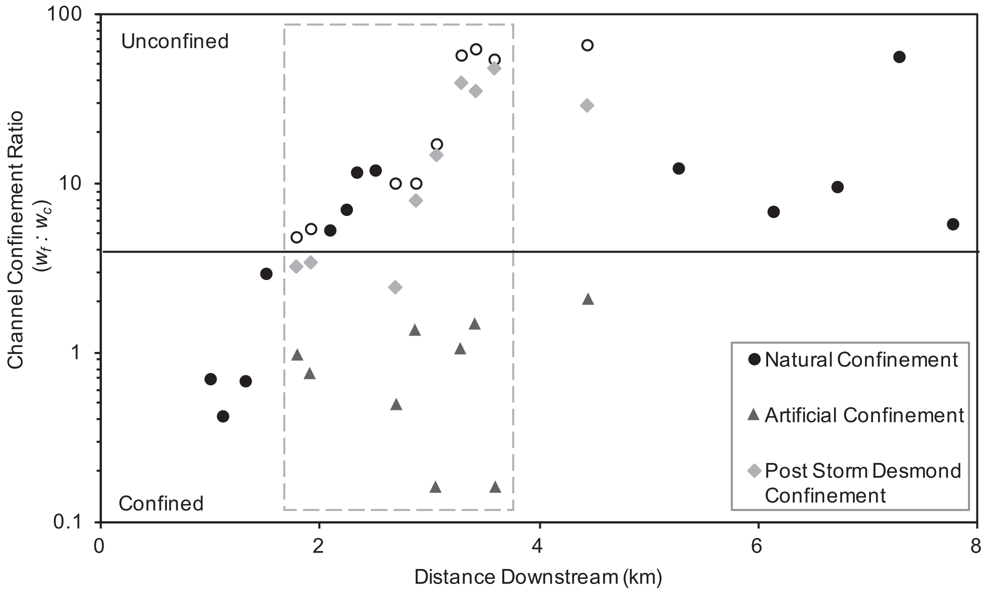


Fig. 9. Natural, artificial and post Storm Desmond lateral channel confinement ratios along St John's Beck. Hollow circles indicate the natural system if the channel was not artificially confined. The dashed box indicates the area where significant sediment erosion and deposition was observed during Storm Desmond. Continuous line indicates the confined and unconfined threshold.

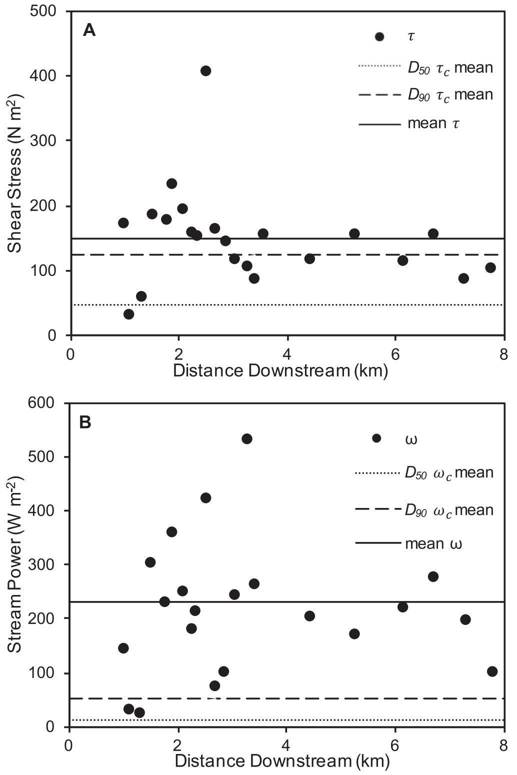


Fig. 10. Variations in reach averaged shear stress (A) and stream power (B) estimated at the cross section sites for Storm Desmond along St John's Beck.

scour was observed 2.5 km downstream where an access bridge was destroyed and where stream power was estimated at 420 W m^{-2}. The mean unit stream power estimate (230 W m^{-2}) exceeds the critical unit stream power value for particle D_{50} (13 W m^{-2}) and D_{90} (54 W m^{-2}) entrainment, suggesting mobilisation of the coarsest grains. The mean unit stream power, estimated using the 2017 data and mean daily discharge, is 0.26 W m^{-2} ± a standard deviation of 0.12 W m^{-2}; this value does not exceed the critical stream power threshold for channel bed particle D_{50} and D_{90} entrainment.

5.4. System resurvey in 2017

Resurveys of St John's Beck longitudinal profile, cross section profiles and grain size in 2017 provide an indication of how the system is recovering 1.5 yr after the extreme flood event (Fig. 11). There were no significant changes in the mean channel bed slope between the 2016 and 2017 survey, however, there were local changes where there is an increase or decrease in bed elevation height (Fig. 11a). Local changes in channel bed elevation result in changes in bankfull channel capacity (Fig. 11b). For example, at a distance of 1 to 2.4 km from Thirlmere Reservoir there is a general increase in bed elevation suggesting the deposition of sediment; a pattern further evidenced by a decrease in channel capacity. Overall a decrease in bankfull channel cross-sectional area was observed (at 15 cross sections) 1.5 yr after Storm Desmond. Thirteen of these cross-sections are located 1 to 2.7 km downstream from Thirlmere Reservoir (Fig. 11b). The largest change and reduction in channel capacity (2.7 km downstream of Thirlmere Reservoir, cross section 11) was 32.8 ± 0.03 m^2 caused by the rebuilding of flood protection levees that reduced channel width to its pre-Storm Desmond size. A total of seven cross-sections displayed either no change or an increase in cross-sectional area and channel capacity. Cross-section 9, 2.4 km downstream from Thirlmere Reservoir, shows an increase in channel capacity associated with anthropogenic removal of sediment from the channel bed after the flood event. The percentage change in grain size between the 2016 and 2017 surveys illustrates a general coarsening of bed D_{50} and fining of D_{90} downstream post Storm Desmond (Fig. 11c).

6. Discussion

6.1. Geomorphic impacts of the extreme flood event along the upland sediment cascade

The 2015 Storm Desmond event constitutes the largest recorded event in the available long term flow and rainfall records for the St John's Beck catchment (Fig. 5). The results presented here illustrate the geomorphic work of the flood in terms of sediment erosion and storage along the upper floodplain transfer zone of the USC. The main impacts were associated with erosion of river channel banks and floodplain scour allied with extensive sediment deposition on the floodplains. The summary sediment budget (Fig. 12) shows erosion (6500 ± 710 t) was generally balanced by deposition (6300 ± 570 t) along the upper floodplain zone. <6% of the total sediment eroded during the event was transferred out of the reach. Hence, the upper floodplain zone acted as a significant sink for locally-eroded sediment during the extreme event.

The geomorphic impacts of Storm Desmond were influenced by the physical characteristics of the upper floodplain transfer zone. Unlike steep headwater catchments dominated by slope-channel linkages and hillslope processes (Harvey, 2001), geomorphic impacts of the event along St John's Beck were controlled by floodplain-channel interactions. Tributaries were only a minor source of sediment as these were disconnected from the channel by sediment trapping structures and therefore are not reported in the sediment budget in Fig. 12. Sediment was sourced from transient stores, i.e., channel bars) and through erosion of the channel bed and banks and stored in channel bars and on the surrounding floodplains (Fig. 6).

Valley confinement (natural and artificial) controlled the spatial positioning of erosional and depositional storm impacts along St John's Beck (Fig. 9). In the upstream reaches (0 to 1.8 km downstream) the channel was confined by the natural valley topography and geomorphic impacts were comprised of local erosion or sediment bar deposition. Where the natural floodplain valley width increases from 3 to 160 m (1.8 km downstream) and there is an associated decrease in channel slope, rapid floodplain sediment deposition occurred (Fig. 7). In contrast, artificially confined reaches (2.7 to 3.6 km downstream) were associated with bank erosion or scour due to local increases in channel bed slope. Major riverbank erosion was observed along an artificially confined reach 2.7 km downstream of Thirlmere Reservoir; here riverbanks were eroded until the channel became unconfined (Fig. 9) with extensive floodplain sedimentation. Similar effects have been observed by Magilligan (1985), Nanson (1986), Butler and Malanson (1993), Lecce (1997), Fuller (2007, 2008), who all identified a concentration of erosion on constricted reaches. The transition between confined and unconfined reaches therefore plays an important role in controlling the spatial pattern of erosion and deposition impacts of these events.

6.2. Sediment continuity through the upland sediment cascade

The sediment continuity concept focuses on the principle of mass conservation of sediment within a system (Slaymaker, 2003; Hinderer, 2012). The USC sediment continuity has been described as a 'jerky conveyor belt', where sediment can spend a longer time in storage than in

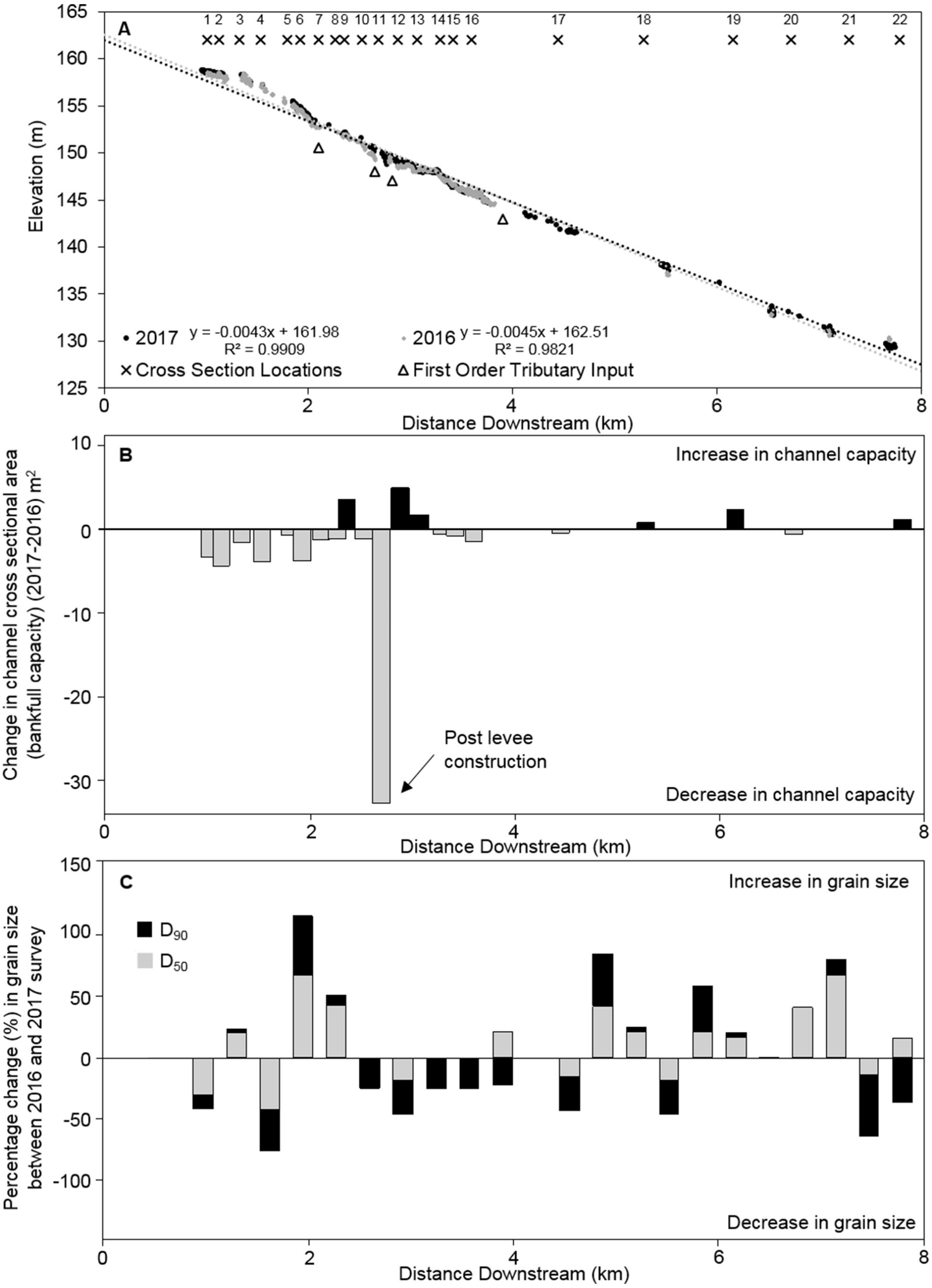


Fig. 11. Changes in St John's Beck channel long profile, bankfull capacity and grain size between the 2016 and 2017 surveys. (A) Change in bed elevation (long profile), labelled with cross section and first order tributary locations. (B) Change in channel bankfull cross section area. (C) Percentage change in channel bed D_{50} and D_{90} grain size.

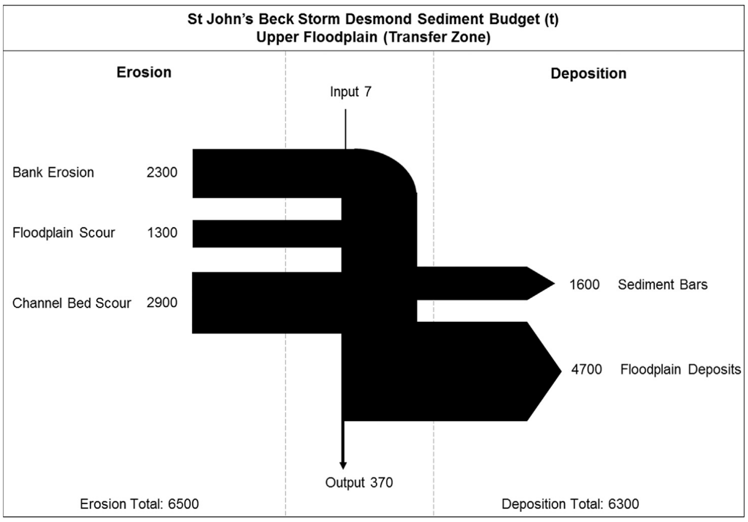


Fig. 12. Storm Desmond (2015) upper floodplain valley system (transfer zone) mass sediment budget (t) for St John's Beck (effective catchment area 12 km^2).

transfer (Ferguson, 1981; Walling, 1983; Newson, 1997; Otto et al., 2009). This study has highlighted that sediment continuity is disrupted or "discontinuous" at the event scale due to storage. <6% of sediment eroded during Storm Desmond was transported out of St John's Beck (Fig. 12). Elsewhere, sediment budget studies have shown similar inefficiencies in sediment transfer, often referring to this as the 'sediment delivery problem' (Trimble, 1983; Walling, 1983; Phillips, 1991; McLean et al., 1999; Fryirs, 2013). For example, in the Coon Creek Basin, USA, <7% of sediment left the basin between 1853 and 1977 (Trimble, 1983). In the River Coquet, UK, annual sediment budget within-reach sediment transfer was identified but there was minimal net export of sediment downstream (Fuller et al., 2002). In three UK upland catchments, Warburton (2010) demonstrated sediment transfer is inefficient in the production zone by comparing sediment budgets on an annual, landslide event and flood event timescale. Despite variations in catchment area and the timescale of enquiry, these examples demonstrate there is attenuation of sediment downstream due to sediment storage. This study highlights the importance of the floodplain as a major store of sediment at the event scale causing sediment attenuation at the channel outlet.

The Storm Desmond event sediment yields were higher than estimated sediment yields for previous flood events along St John's Beck (Table 3), indicating the event was significant in generating and transporting large quantities of sediment downstream. The estimated mean shear stress and unit stream power values for Storm Desmond exceeded the thresholds for particle entrainment, suggesting sediment on the channel bed was mobilised and transported during the event (Fig. 10). Despite this, the event sediment yield is lower than the total quantity of sediment eroded. Sediment transfer during extreme events, where overbank flows are produced, is reduced on the floodplains (because of variations in roughness, slope, local topography) compared to the channel, resulting in sediment deposition (Trimble, 1983; Moore and Newson, 1986). Consequently, sediment continuity through the upper floodplain transfer zone during extreme events will ultimately be controlled by the conveyance of sediment across floodplains, and the propensity for sediment deposition during overbank flows. Future flood events may promote exchanges in sediment stores and movement of sediment downstream in pulses or waves, thereby influencing sediment yield (Nicholas et al., 1995). However, if a future similar magnitude event were to occur along St John's Beck, it is likely that the reach sediment output would again be lower than the total sediment eroded along the river corridor due to deposition on the floodplains.

Previous studies have described the potential linkages between sources and stores of sediment in terms of connectivity or disconnectivity (Hooke, 2003; Fryirs, 2013; Bracken et al., 2015). However, few of these studies have quantified the mass exchange of sediment between different landscape units during flood events (Thompson et al., 2016) and assessed their impact on sediment yield. This study is among the first to effectively quantify sediment attenuation in the upper floodplain zone of the USC during an extreme event.

6.3. System recovery

Fluvial systems can take decades (Wolman and Gerson, 1978; Sloan et al., 2001) to millennia (Lancaster and Casebeer, 2007) to recover from extreme events, with some systems never fully recovering to the pre-flood condition. The channel re-survey one year after Storm Desmond showed that 70% of cross sections had a reduced channel capacity reflecting sediment aggradation in the channel (Fig. 11). A reconnaissance survey prior to Storm Desmond identified distinct reaches of sediment aggradation in the system (in particular, 2 to 2.5 km downstream of Thirlmere Reservoir), suggesting the river is displaying characteristics similar to the pre-flood system. Long term flow regulation and upstream sediment trapping by Thirlmere Reservoir has influenced sediment continuity, implying that the sediment regime is already disturbed by the legacy of anthropogenic modification (Wohl, 2015). Phillips (1991) states that stores of sediment may develop in fluvial systems so the system can maintain sediment yields when sediment from upstream is reduced. The critical shear stress and critical stream power entrainment thresholds for channel bed particle D_{90} estimated using the 2017 survey data were not exceeded during daily flows after storm Desmond indicting coarse sediment immobility. It is likely that the finer material was transported in 2017 and deposited downstream in aggradational zones where channel dimensions change (i.e., reduction in slope, width and depth), resulting in further aggradation downstream and apparent coarsening in reaches where the fine sediment was partially mobilised. Therefore local aggradation observed could be a response to long-term system disturbance and transport-limited flows.

The most significant changes observed along St John's Beck one year after the flood were associated with anthropogenic modifications to the system through the rebuilding of flood protection levees, reinforced river banks and removal of sediment from the channel bed and floodplains (2 to 4 km downstream); these modifications took place after the 2016 field campaign. Distal floodplain deposits were located 70 m from the channel and therefore can only be remobilised during overbank flows with similar peak discharges where the critical entrainment thresholds are exceeded. Consequently, system recovery and sediment transfer depends on the conveyance capacity of the valley floodplains in addition to the stream channel capacity (Trimble, 2010). If sediment was not anthropogenically removed from the floodplains, it would have a long residence time in this store and only be remobilised during overbank extreme flows similar to Storm Desmond. Flood levees were rebuilt 2.7 km downstream to the pre-flood position, it is likely that if these levees were not restored the river would permanently occupy the post-Storm Desmond position; a natural "re-wilding" process (Fryirs and Brierley, 2016).

7. Conclusions

This paper has quantified the geomorphic response of an upper floodplain river system (transfer zone) to an extreme high magnitude flood event: Storm Desmond, 2015. The results highlight that sediment continuity along upland rivers is complex and to fully understand the response of these systems to extreme events, sediment continuity in the context of the upland sediment cascade needs to be understood (Fig. 1). Based on our results, the primary conclusions of this work are:

1. Sediment continuity through the upper floodplain transfer zone was highly disrupted during Storm Desmond, with <6% of the eroded sediment being transported out of the system.
2. Floodplains acted as a major sink of coarse sediment during the flood, storing 72% of the eroded sediment, although these floodplains can also be a source of sediment through scouring and erosion processes.
3. Spatial patterns of erosion and deposition were controlled by valley confinement; where the channel is naturally unconfined overbank floodplain deposits were prominent, in contrast, in artificially-confined reaches, bank erosion and scour were dominant geomorphic impacts.
4. The event exceeded critical entrainment thresholds for channel bed particle D_{50} and D_{90} transporting sediment that had aggraded in the channel. Critical entrainment thresholds were not exceeded during daily flows for all particle sizes along St John's Beck in the 2017 survey.
5. Channel capacity decreased 1.5 yr after the event and channel bed grain size had coarsened due to aggradation in the channel.

This study has quantified the importance of the upper floodplain zone in regulating sediment output during extreme events. The results suggest that rather than envisioning upper floodplain zones as effective transfer reaches they are actually major storage zones that capture flood sediments and disrupt sediment continuity downstream. The intervening valley floodplain geomorphology (confinement, slope) plays a major role in influencing the spatial location of erosion and deposition impacts.

Acknowledgements

The authors thank Graham, Sarah and William Chaplin-Bryce and their family for allowing access to St John's Beck and for valuable discussions of their experience of the Storm Desmond flood and the history of the river. A. Cartwright, G. Paxman, V. Smith and R. Smith are all thanked for their help collecting the field data at various stages. Thanks are due to the Environment Agency for supplying aerial photograph, rainfall and discharge data. Hannah M. Joyce was funded by a Natural Environmental Research Council UK Studentship Grant Number NE/L002590/1. Jeff Warburton was supported by a Natural Environmental Research Council Urgency Grant NE/P000118/1.

Funding

This work was supported by the Natural Environmental Research Council [grant number, NE/L002590/1].

References

Ashbridge, D., 1995. Processes of river bank erosion and their contribution to the suspended sediment load of the River Culm, Devon. In: Foster, I., Gurnell, A., Webb, B. (Eds.), Sediment and Water Quality in River Catchments. John Wiley and Sons, Chichester, pp. 229–245.
Bagnold, R.A., 1966. An approach to the sediment transport problem from general physics. U.S. Geological Survey Proffessional Paper 422-I. United States Government Printing Office, Washington.
Baker, V., Costa, J., 1987. Flood power. In: Mayer, L., Nash, D. (Eds.), Catastrophic Flooding. Allen and Unwin, Boston, pp. 1–20.
BBC, 2016. Flood-hit A591: Closure 'to cost Lake District £1m a day'. http://www.bbc.co.uk/news/uk-england-cumbria-35547704 (Last Accessed: 13/10/2017).
Bracken, L.J., Turnbull, L., Wainwright, J., Bogaart, P., 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. Earth Surf. Process. Landf. 40 (2), 177–188.
Brewer, P.A., Passmore, D.G., 2002. Sediment budgeting techniques in gravel-bed rivers. Geol. Soc. Lond., Spec. Publ. 191 (1), 97–113.
Bromley, J., 2015. Thirlmere Catchment Sediment Management Plan. United Utilities, Warrington, p. 37.
Burt, T., Allison, R.J., 2010. Sediment Cascades: An Integrated Approach. John Wiley and Sons, Chichester.
Butler, D.R., Malanson, G.P., 1993. An unusual early-winter flood and its varying geomorphic impact along a subalpine river in the Rocky Mountains. Z. Geomorphol. 37 (2), 145–155.
Caine, N., Swanson, F., 2013. Geomorphic coupling of hillslope and channel systems in two small mountain basins. In: Slaymaker, O. (Ed.), Geomorphology: Critical Concepts in Geography. Routledge, Oxon, pp. 159–173.
Carling, P., 1987. Bed Stability in Gravel Streams, with Reference to Stream Regulation and Ecology. River Channels: Environment and Process. Blackwell Scientific Publications, Oxford, UK, pp. 321–347.
Carling, P., 1988. The concept of dominant discharge applied to two gravel-bed streams in relation to channel stability thresholds. Earth Surf. Process. Landf. 13 (4), 355–367.
CEH, 2015. North West Floods - Hydrological Update. https://www.ceh.ac.uk/news-and-media/blogs/north-west-floods-hydrological-update.
Chorley, R.J., Kennedy, B.A., 1971. Physical Geography: A Systems Approach. Prentice-Hall International, London.
Chow, T.V., 1959. Open-channel Hydraulics. McGraw-Hill Inc, New York.
Church, M., 2002. Geomorphic thresholds in riverine landscapes. Freshw. Biol. 47 (4), 541–557.
Crozier, M.J., 2010. Landslide geomorphology: an argument for recognition, with examples from New Zealand. Geomorphology 120 (1–2), 3–15.
Davies, T.R., Korup, O., 2010. Sediment cascades in active landscapes. In: Burt, T., Allison, R.J. (Eds.), Sediment Cascades: An Integrated Approach. John Wiley and Sons, Chichester, pp. 89–115.
Digimap, Edina, 2016. EDINA Digimap Data Collection. https://digimap.edina.ac.uk/.
Du Boys, M., 1879. The Rhone and streams with movable beds. Ann. Ponts Chaussees 18, 141–195.
Environment Agency, 2006. Cumbria floods technical report. Factural report on meterology, hydrology and impacts of the January 2005 flooding in Cumbria. http://www.bramptonweather.co.uk/data/CarlisleFloods2005.pdf.
Ferguson, R.I., 1981. Channel forms and channel changes. In: Lewin, J. (Ed.), British Rivers. George Allen and Unwin, London, pp. 90–125.
Foster, I.D., 2010. Lakes and reservoirs in the sediment cascade. In: Burt, T., Allison, R.J. (Eds.), Sediment Cascades: An Integrated Approach. John Wiley and Sons, Chichester, pp. 345–376.
Fryirs, K., 2013. (Dis)connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. Earth Surf. Process. Landf. 38 (1), 30–46.
Fryirs, K.A., Brierley, G.J., 2016. Assessing the geomorphic recovery potential of rivers: forecasting future trajectories of adjustment for use in management. Wiley Interdisciplinary Reviews: Water. 3(5), pp. 727–748.
Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M., 2007. Buffers, barriers and blankets: the (dis)connectivity of catchment-scale sediment cascades. Catena 70 (1), 49–67.
Fuller, I.C., 2007. Geomorphic work during a "150-year" storm: contrasting behaviors of river channels in a New Zealand catchment. Ann. Assoc. Am. Geogr. 97 (4), 665–676.
Fuller, I.C., 2008. Geomorphic impacts of a 100-year flood: Kiwitea Stream, Manawatu catchment, New Zealand. Geomorphology 98 (1), 84–95.
Fuller, I., Passmore, D., Heritage, G., Large, A., Milan, D., Brewer, P., 2002. Annual sediment budgets in an unstable gravel-bed river: the river coquet, northern England. Geol. Soc. Lond., Spec. Publ. 191 (1), 115–131.
Fuller, I.C., Large, A.R.G., Charlton, M.E., Heritage, G.L., Milan, D.J., 2003. Reach-scale sediment transfers: an evaluation of two morphological budgeting approaches. Earth Surf. Process. Landf. 28 (8), 889–903.
Fuller, I.C., Riedler, R.A., Bell, R., Marden, M., Glade, T., 2016. Landslide-driven erosion and slope-channel coupling in steep, forested terrain, Ruahine Ranges, New Zealand, 1946–2011. Catena 142, 252–268.
Gellis, A.C., Myers, M.K., Noe, G.B., Hupp, C.R., Schenk, E.R., Myers, L., 2017. Storms, channel changes, and a sediment budget for an urban-suburban stream, difficult run, Virginia, USA. Geomorphology 278, 128–148.

Gergel, S.E., Dixon, M.D., Turner, M.G., 2002. Consequences of human-altered floods: levees, floods, and floodplain forests along the Wisconsin River. Ecol. Appl. 12 (6), 1755–1770.
Gordon, N.D., McMahon, T.A., Finlayson, B.L., 1992. Sediment Motion, Stream Hydrology: An Introduction for Ecologists. John Wiley and Sons, Chichester, pp. 324–336.
Gurnell, A.M., 1983. Downstream channel adjustments in response to water abstraction for hydro-electric power generation from alpine glacial melt-water streams. Geogr. J. 149 (3), 342–354.
Hall, J.E., Holzer, D.M., Beechie, T.J., 2007. Predicting river floodplain and lateral channel migration for salmon habitat conservation. J. Am. Water Resour. Assoc. 43 (3), 786–797.
Harvey, A.M., 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill fells, Northwest England. Catena 42 (2–4), 225–250.
Harvey, A.M., 2007. Differential recovery from the effects of a 100-year storm: significance of long-term hillslope–channel coupling; Howgill fells, Northwest England. Geomorphology 84 (3–4), 192–208.
Herdendorf, C.E., 1982. Large lakes of the world. J. Great Lakes Res. 8 (3), 379–412.
Hey, R., Winterbottom, A., 1990. River engineering in National Parks: the case of the River Wharfe, UK. Regulated Rivers. Res. Manag. 5 (1), 35–44.
Hinderer, M., 2012. From gullies to mountain belts: a review of sediment budgets at various scales. Sediment. Geol. 280, 21–59.
Hooke, J., 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. Geomorphology 56 (1), 79–94.
Johnson, R.M., Warburton, J., 2002. Flooding and geomorphic impacts in a mountain torrent: raise Beck, Central Lake District, England. Earth Surf. Process. Landf. 27 (9), 945–969.
Johnson, R.M., Warburton, J., 2006. Variability in sediment supply, transfer and deposition in an upland torrent system: Iron crag, northern England. Earth Surf. Process. Landf. 31 (7), 844–861.
Johnson, R., Warburton, J., Mills, A., 2008. Hillslope–channel sediment transfer in a slope failure event: wet swine gill, Lake District, northern England. Earth Surf. Process. Landf. 33 (3), 394–413.
Knighton, D., 1998. Fluvial Forms and Processes: A New Perspective. Arnold, London.
Knox, J.C., 2006. Floodplain sedimentation in the upper Mississippi Valley: natural versus human accelerated. Geomorphology 79 (3), 286–310.
Kondolf, G.M., 1997. PROFILE: hungry water: effects of dams and gravel mining on river channels. Environ. Manag. 21 (4), 533–551.
Kondolf, G.M., Matthews, W.V.G., 1991. Unmeasured residuals in sediment budgets – a cautionary note. Water Resour. Res. 27 (9), 2483–2486.
Korup, O., 2005. Geomorphic imprint of landslides on alpine river systems, Southwest New Zealand. Earth Surf. Process. Landf. 30 (7), 783–800.
Korup, O., 2012. Earth's portfolio of extreme sediment transport events. Earth Sci. Rev. 112 (3–4), 115–125.
Krapesch, G., Hauer, C., Habersack, H., 2011. Scale orientated analysis of river width changes due to extreme flood hazards. Nat. Hazards Earth Syst. Sci. 11 (8), 2137.
Lancaster, S.T., Casebeer, N.E., 2007. Sediment storage and evacuation in headwater valleys at the transition between debris-flow and fluvial processes. Geology 35 (11), 1027–1030.
Langhammer, J., 2010. Analysis of the relationship between the stream regulations and the geomorphologic effects of floods. Nat. Hazards 54 (1), 121–139.
Lecce, S.A., 1997. Spatial patterns of historical overbank sedimentation and floodplain evolution, Blue River, Wisconsin. Geomorphology 18 (3–4), 265–277.
Lewin, J., 1981. British Rivers. George Allen and Unwin, London.
Lewin, J., 2013. Enlightenment and the GM floodplain. Earth Surf. Process. Landf. 38 (1), 17–29.
Lisenby, P.E., Croke, J., Fryirs, K.A., 2018. Geomorphic effectiveness: a linear concept in a non-linear world. Earth Surf. Process. Landf. 43 (1), 4–20.
Magilligan, F.J., 1985. Historical floodplain sedimentation in the Galena River basin, Wisconsin and Illinois. Ann. Assoc. Am. Geogr. 75 (4), 583–594.
Magilligan, F.J., 1992. Thresholds and the spatial variability of flood power during extreme floods. Geomorphology 5 (3–5), 373–390.
Marchi, L., Cavalli, M., Amponsah, W., Borga, M., Crema, S., 2016. Upper limits of flash flood stream power in Europe. Geomorphology 272, 68–77.
McCarthy, M., Spillane, S., Walsh, S., Kendon, M., 2016. The meteorology of the exceptional winter of 2015/2016 across the UK and Ireland. Weather 71 (12), 305–313.
McDougall, D., Evans, D., 2015. The Quaternary of the Lake District Field Guide. Quaternary Research Association.
McLean, D.G., Church, M., Tassone, B., 1999. Sediment transport along lower Fraser River - 1. Measurements and hydraulic computations. Water Resour. Res. 35 (8), 2533–2548.
Met Office, 2016. Flooding in Cumbria December 2015. https://www.metoffice.gov.uk/climate/uk/interesting/december2015, Accessed date: February 2018.
Milan, D.J., 2012. Geomorphic impact and system recovery following an extreme flood in an upland stream: Thinhope burn, northern England, UK. Geomorphology 138 (1), 319–328.
Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic tectonic control of sediment discharge to the ocean - the importance of small mountainous rivers. J. Geol. 100 (5), 525–544.
Montgomery, D.R., Buffington, J.M., 1993. Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition. Department of Geological Sciences and Quaternary Research Centre. University of Washington, Washington.
Moore, R.J., Newson, M.D., 1986. Production, storage and output of coarse upland sediments - natural and artificial influences as revealed by research catchment studies. J. Geol. Soc. Lond. 143, 921–926.
Nagel, D.E., Buffington, J.M., Parkes, S.L., Wenger, S., Goode, J.R., 2014. A Landscape Scale Valley Confinement Algorithm: Delineating Unconfined Valley Bottoms for Geomorphic, Aquatic, and Riparian Applications. Rocky Mountain Research Station Fort Collins, US Department of Agriculture, Forest Service.
Nanson, G.C., 1986. Episodes of vertical accretion and catastrophic stripping: a model of disequilibrium flood-plain development. Geol. Soc. Am. Bull. 97 (12), 1467–1475.
Newson, M., 1997. Time, scale and change in river landscapes: the jerky conveyor belt. Landsc. Res. 22 (1), 13–23.
Nicholas, A., Ashworth, P., Kirkby, M., Macklin, M., Murray, T., 1995. Sediment slugs: large-scale fluctuations in fluvial sediment transport rates and storage volumes. Prog. Phys. Geogr. 19 (4), 500–519.
Odgaard, A.J., 1987. Streambank erosion along two rivers in Iowa. Water Resour. Res. 23 (7), 1225–1236.
van Oldenborgh, G.J., Otto, F.E., Haustein, K., Cullen, H., 2015. Climate change increases the probability of heavy rains like those of storm Desmond in the UK-an event attribution study in near-real time. Hydrology & Earth System Sciences Discussions. 12(12).
Otto, J.C., Schrott, L., Jaboyedoff, M., Dikau, R., 2009. Quantifying sediment storage in a high alpine valley (Turtmanntal, Switzerland). Earth Surf. Process. Landf. 34 (13), 1726–1742.
Petit, F., Gob, F., Houbrechts, G., Assani, A., 2005. Critical specific stream power in gravel-bed rivers. Geomorphology 69 (1–4), 92–101.
Petts, G.E., 1979. Complex response of river channel morphology subsequent to reservoir construction. Prog. Phys. Geogr. 3 (3), 329–362.
Petts, G.E., Gurnell, A.M., 2005. Dams and geomorphology: research progress and future directions. Geomorphology 71 (1), 27–47.
Petts, G.E., Thoms, M.C., 1986. Channel aggradation below Chew valley lake, Somerset, UK. Catena 13 (3), 305–320.
Phillips, J.D., 1991. Fluvial sediment budgets in the North-Carolina piedmont. Geomorphology 4 (3–4), 231–241.
Pitlick, J., Cui, Y., Wilcock, P., 2009. Manual for Computing Bed Load Transport Using BAGS (Bedload Assessment for Gravel-Bed Streams) Software.
Prosser, I.P., Hughes, A.O., Rutherfurd, I.D., 2000. Bank erosion of an incised upland channel by subaerial processes: Tasmania, Australia. Earth Surf. Process. Landf. 25 (10), 1085–1101.
Raven, E.K., Lane, S.N., Bracken, L.J., 2010. Understanding sediment transfer and morphological change for managing upland gravel-bed rivers. Prog. Phys. Geogr. 34 (1), x23–45.
Reid, H., 2014. Thirlmere Gravel Management. Environment Agency, Cumbria, p. 23.
Reid, L.M., Dunne, T., 1996. Rapid Evaluation of Sediment Budgets. 29. Catena Reiskirchen, Germany.
Reid, L.M., Dunne, T., 2003. Sediment budgets as an organizing framework in fluvial geomorphology. Tools in fluvial. Geomorphology 357–380.
Righini, M., Surian, N., Wohl, E., Marchi, L., Comiti, F., Amponsah, W., Borga, M., 2017. Geomorphic response to an extreme flood in two Mediterranean rivers (northeastern Sardinia, Italy): analysis of controlling factors. Geomorphology 290, 184–199.
Roberts, N.M., Cole, S.J., Forbes, R.M., Moore, R.J., Boswell, D., 2009. Use of high-resolution NWP rainfall and river flow forecasts for advance warning of the Carlisle flood, northwest England. Meteorol. Appl. 16 (1), 23–34.
Schumm, S.A., 1977. The Fluvial System. John Wiley and Sons, New York.
Sear, D., Wheaton, J., Neal, J., Andersen, E., Leyalnd, J., Hornby, D., Bates, P., Murdoch, A., Dearing, J., 2017. Valley and Human Controls on the Geomorphic Responses to an Extreme Flood, Cumbrian Floods Partnership Geomorphology Workshop. Penrith, UK.
Sibley, A., 2010. Analysis of extreme rainfall and flooding in Cumbria 18–20 November 2009. Weather 65 (11), 287–292.
Slaymaker, O., 1991. Mountain geomorphology: a theoretical framework for measurement programmes. Catena 18 (5), 427–437.
Slaymaker, O., 2003. The sediment budget as conceptual framework and management tool. The Interactions Between Sediments and Water. Springer, pp. 71–82.
Sloan, J., Miller, J.R., Lancaster, N., 2001. Response and recovery of the Eel River, California, and its tributaries to floods in 1955, 1964, and 1997. Geomorphology 36 (3), 129–154.
Smith, G., 1754. Dreadful storm in Cumberland. Gentleman's Magazine 24, 464–467.
Smith, H.G., Dragovich, D., 2008. Sediment budget analysis of slope–channel coupling and in-channel sediment storage in an upland catchment, southeastern Australia. Geomorphology 101 (4), 643–654.
Stewart, L., Morris, D., Jones, D., Spencer, P., 2010. Extreme Rainfall in Cumbria, November 2009-an Assessment of Storm Rarity, BHS Third International Symposium, Managing Consequences of a Changing Global Environment, Newcastle.
Stewart, L., Vesuviano, G., Morris, D., Prosdocimi, I., 2014. The new FEH rainfall depth-duration-frequency model: results, comparisons and implications. [Speech]. 12th British Hydrological Society National Symposium, Birmingham, UK, 2–4 Sept 2014.
Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topography. Geol. Soc. Am. Bull. 63 (11), 1117–1142.
Thompson, C., Croke, J., 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer valley, Southeast Queensland, Australia. Geomorphology 197, 156–169.
Thompson, C.J., Fryirs, K., Croke, J., 2016. The disconnected sediment conveyor belt: patterns of longitudinal and lateral erosion and deposition during a catastrophic flood in the Lockyer Valley, South East Queensland, Australia. River Res. Appl. 32 (4), 540–551.
Thorne, C.R., 1998. Stream Reconnaissance Guidebook: Geomorphological Investigation and Analysis of River Channels. John Wiley & Sons, Chichester, UK.
Trimble, S.W., 1983. A sediment budget for Coon Creek basin in the Driftless area, Wisconsin, 1853–1977. Am. J. Sci. 283 (5), 454–474.
Trimble, S.W., 2010. Streams, valleys and floodplains in the sediment cascade. In: Burt, T., Allison, R.J. (Eds.), Sediment Cascades: An Integrated Approach. John Wiley and Sons, Chichester, pp. 307–343.

Wallace, M., Atkins, J., 1997. A Medium Term Study of the Salmonid Populations in St John's Beck and the River Glenderamackin (River Derwent, Cumbria) 1974 to 1996. Environment Agency, Cumbria.
Walling, D.E., 1983. The sediment delivery problem. J. Hydrol. 65 (1–3), 209–237.
Warburton, J., 2010. Sediment transfer in steep upland catchments (Northern England, UK): landform and sediment source coupling. In: Otto, J.-C., Dikau, R. (Eds.), Landform – Structure, Evolution, Process Control. Lecture Notes in Earth Sciences. Springer Berlin Heidelberg, pp. 165–183.
Warburton, J., Kincey, M., Johnson, R.M., 2016. Assessment of Torrent Erosion Impacts on the Eastern Flank of Thirlmere Reservoir and A591 (Cumbria) Following Storm Desmond 2015. Durham University, Durham.
Watkins, S., Whyte, I., 2008. Extreme flood events in upland catchments in Cumbria since 1600: the evidence of historical records. North West. Geography 8 (1), 33–41.
Watts, G., Battarbee, R.W., Bloomfield, J.P., Crossman, J., Daccache, A., Durance, I., Elliott, J.A., Garner, G., Hannaford, J., Hannah, D.M., 2015. Climate change and water in the UK–past changes and future prospects. Prog. Phys. Geogr. 39 (1), 6–28.
Wicherski, W., Dethier, D.P., Ouimet, W.B., 2017. Erosion and channel changes due to extreme flooding in the Fourmile Creek catchment, Colorado. Geomorphology 294, 87–98.
Wilcock, P.R., Crowe, J.C., 2003. Surface-based transport model for mixed-size sediment. J. Hydraul. Eng. 129 (2), 120–128.
Williams, G.P., 1983. Paleohydrological methods and some examples from Swedish fluvial environments: I cobble and boulder deposits. Geografiska Annaler: Series A. Phys. Geogr. 65 (3–4), 227–243.
Williams, G., Costa, J., 1988. Geomorphic measurements after a flood. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. John Wiley and Sons, Canada, pp. 65–80.
Williams, G.P., Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers. U.S. Geological Survey Professional Paper 1286. U.S. Government Printing Office, Washington.
Wohl, E., 2015. Legacy effects on sediments in river corridors. Earth Sci. Rev. 147, 30–53.
Wolman, M.G., 1954. A method of sampling coarse river-bed material. EOS Trans. Am. Geophys. Union 35 (6), 951–956.
Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surf. Process. Landf. 3 (2), 189–208.

Appendix B

Published paper:

Joyce, H.M., Warburton, J., Hardy, R.J., (2020). A catchment scale assessment of patterns and controls of historic 2D river planform adjustment. Geomorphology https://doi.org/10.1016/j.geomorph.2020.107046

Geomorphology 354 (2020) 107046

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

A catchment scale assessment of patterns and controls of historic 2D river planform adjustment

Hannah M. Joyce *, Jeff Warburton, Richard J. Hardy

Department of Geography, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE, UK

ARTICLE INFO

Article history:
Received 7 September 2019
Received in revised form 15 January 2020
Accepted 16 January 2020
Available online 22 January 2020

Keywords:
Catchment scale
Channel planform adjustment
Upland rivers
Stream order
Spatial analysis

ABSTRACT

The supply, transfer and deposition of sediment from channel headwaters to lowland sinks, is a fundamental process governing upland catchment geomorphology, and can begin to be understood by quantifying 2D river planform adjustments over time. This paper presents a catchment scale methodology to quantify historic patterns of 2D channel planform adjustment and considers geomorphic controls on 2D river stability. The methodology is applied to 18 rivers (total length = 24 km) in the upland headwaters of the previously glaciated Wasdale catchment (45 km^2), Lake District, northwest England. Planform adjustments were mapped from historic maps and air photographs over six contiguous time windows covering the last 150 yr. A total of 1048 adjustment and stable reaches were mapped. Over the full period of analysis (1860–2010) 32% (8 km) of the channels studied were adjusting. Contrasts were identified between the geomorphic characteristics (slope, catchment area, unit specific stream power, channel width and valley bottom width) of adjusting and stable reaches. The majority of adjustments mapped were observed in third and fourth order channels in the floodplain valley transfer zone, where the channels were laterally unconfined (mean valley bottom widths of 230 ± 180 m), with low sediment continuity. In contrast, lower order channels were typically confined (mean valley bottom widths of 31 ± 43 m) and showed relative 2D lateral stability. Hence, valley bottom width was found to be important in determining the available space for rivers to adjust. Over the full period of analysis 38% of planform adjustments involved combined processes, for example, as bar and bend adjustments. The study demonstrates the importance of stream network hierarchy in determining spatial patterns of historic planform adjustments at the catchment scale. The methodology developed provides a quantitative assessment of planform adjustment patterns and geomorphic controls, which is needed to support the prioritisation of future river management and restoration.

1. Introduction

Systematic assessment of the spatial and temporal patterns of river planform adjustments provides important insights for understanding current and potential future river behaviour (Hooke and Redmond, 1989a; Winterbottom, 2000; Brierley and Fryirs, 2005a; Lisenby and Fryirs, 2016; Rinaldi et al., 2016). This is because channels adjust through erosion, transfer and deposition of sediment (Lewin, 1977; Thorne, 1997) and therefore, channel planform adjustments reflect sediment continuity. Sediment continuity is defined as the conservation of mass between fluvial sediment inputs, storage and outputs in a river system (Joyce et al., 2018). Contemporary channel planform is a consequence of the legacy of past and present, exogenic and endogenic forces, controlling water and sediment continuity across a catchment (Schumm, 1977; Ferguson, 1987; Newson, 1997; Sear et al., 2003; Joyce et al., 2018; Bizzi et al., 2019). However, few studies (Hooke and Redmond, 1989a; Wishart, 2004; Lisenby and Fryirs, 2016) have adopted rigorous quantitative assessments of channel planform adjustment and stability at the catchment scale over historical time periods.

To understand the spatial and temporal pattern of planform adjustments and sediment continuity it is important to quantify the variables controlling planform stability (Martínez-Fernández et al., 2019). Climate influences the frequency and magnitude of flood events, and therefore the stream power available to erode and transport sediment (Newson, 1980; Wolman and Miller, 1960; Milne, 1982; McEwen, 1994; Rumsby and Macklin, 1994; Werritty and Leys, 2001; Johnson and Warburton, 2002; Surian et al., 2016). Geological and geomorphological processes (Higgitt et al., 2001) determine availability of sediment, sediment type, topographic confinement, the presence of lakes and channel slope (Milne, 1983; Fryirs et al., 2016). Anthropogenic activity influences the flow regime (Petts, 1979; Kondolf, 1997), sediment supply (Heckmann et al., 2017), and space available for planform adjustment (Gilvear and Winterbottom, 1992; Surian and Rinaldi, 2003). Channels adjust in response to these collective controls.

Two dimensional planform adjustments can be readily identified from historic maps and air photographs over the last century (the period of 'measurable change') when such resources are available. This

* Corresponding author.
E-mail address: hannah.joyce@durham.ac.uk (H.M. Joyce).

https://doi.org/10.1016/j.geomorph.2020.107046

provides a suitable time span to understand planform adjustments in response to recent changes in climate and land use (Schumm and Lichty, 1965; Hooke and Redmond, 1989b; Winterbottom, 2000; Higgitt et al., 2001). However, there is no consistent quantitative methodology that applies a catchment wide assessment of the temporal patterns of planform adjustment from channel headwaters to lowland sediment sinks (Bizzi et al., 2019). Traditionally, channel planform adjustments have been investigated at the reach scale at locations of instability in high stream order channels in the transfer zone of the sediment cascade (Schumm, 1969; Lewin and Hughes, 1976; Lewin, 1977; Lewin et al., 1977; Blacknell, 1981; Milne, 1982; Milne, 1983; Warburton et al., 2002; Wishart et al., 2008; Hooke and Yorke, 2010). These studies often fail to characterise the spatial and temporal patterns of sediment continuity because: (i) active adjustment reaches are not evaluated in the broader catchment context, for example along the entire length of a river or between rivers in the same catchment where similar geomorphic conditions occur (Fryirs et al., 2009; Gurnell et al., 2016); (ii) the historic pattern of channel adjustment and stability is not assessed; and (iii) the geomorphic characteristics of both stable and active channel reaches are not quantified, which is needed to explain and identify the locations susceptible to future adjustment.

The benefit of spatial planform adjustment studies is widely recognised (Hooke and Redmond, 1989a; Rosgen, 1994; Macklin et al., 1998; Wishart, 2004; Lisenby and Fryirs, 2016; England and Gurnell, 2016), and is reinforced by recent European and UK legislation, which emphasise the need for integrated and catchment wide assessments of the hydro-morphological condition of rivers (c.f. European Water Framework Directive (European Commission, 2000); Floods Directive (European Commission, 2007) and UK governmental 25 yr Environmental Plan). Hierarchical river and catchment characterisation approaches (Brierley and Fryirs, 2005b; Rinaldi et al., 2015a; Gurnell et al., 2016) and the use of remotely sensed data (Marcus and Fonstad, 2010; Bizzi et al., 2019) have provided an important step towards understanding channel planform types at the catchment scale (Brierley and Fryirs, 2005a, 2005b). However, hierarchical approaches are often qualitative, use complex scoring indexes to characterise river types (Rinaldi et al., 2013; Rinaldi et al., 2015a; Rinaldi et al., 2015b), do not directly quantify the temporal trajectory of planform adjustment and fail to capture the geomorphic variables of planform adjustment and stability within the overall catchment structure (Lisenby and Fryirs, 2016).

This paper presents a catchment-wide methodology to quantitatively assess the patterns and geomorphic variables of historic 2D river planform adjustments within a sediment continuity framework. The specific objectives of the methodology are: (i) to quantify the spatial pattern of 2D channel planform adjustment over the era of measurable change (last 150 yr), (ii) quantify the geomorphic variables forcing 2D channel planform adjustments, and (iii) use data from (i) and (ii) to understand spatial and temporal patterns of 2D channel planform adjustments at the catchment scale. The method is applied and tested in the Wasdale catchment in the Lake District, northwest England. This catchment is selected because it exhibits a rich variety of fluvial forms including: bedrock, confined, unconfined wandering and braided channels (Harvey, 1997), and has available historic data.

2. Methodology

The methodology proposed here quantifies 2D historic channel planform dynamics in headwater catchments. The method is structured on Strahler's (1952, 1957) stream order to reflect the natural scaling of geomorphic variables: catchment area, channel width, length, slope, stream power and valley bottom width (Leopold and Miller, 1956; Strahler, 1957; Miller et al., 2002; Hughes et al., 2011). The approach is applied at the catchment scale and comparisons are made between stream orders in a similar regional setting. The method uses commonly available datasets, including: digital terrain models (DTM), air photos, historic topographic maps, bedrock and superficial geology data, which are analysed in a Geographical Information System (GIS) package (Fig. 1). These data requirements allow 2D patterns of river planform adjustment to be identified, and 1D and 2D catchment geomorphic variables to be extracted. The workflow is summarised in Fig. 1.

2.1. Part 1: Pre-processing - assembly of data and identification of spatial scales

The methodology takes a top-down perspective working down the sediment cascade from upland channel headwaters to a point where the river channel enters either a major lowland valley waterbody (lake) or, if no water body is present, an endpoint is defined at a point in the lowland valley. In UK upland regions, the lowland valley is commonly defined where the river channel network is no longer surrounded by hillslopes above 300 m elevation (Atherden, 1992).

The catchment, river channel network and Strahler (1952, 1957) stream order are first defined using a high-resolution DTM and automated flow delineation tools in GIS. The stream order network provides a stratified framework in which the spatial location, length and type of planform adjustments observed between the temporal data (historic maps/air photographs) are mapped (Part 2B).

The time interval and frequency over which 2D planform adjustments can be identified depends on the availability of data. In the UK, studies of channel planform adjustments can, in some cases, be identified from sources dating from the sixteenth century to present (Lewin, 1987; Macklin and Lewin, 1989; Petts et al., 1989; Macklin et al., 1992; Downward et al., 1994; Milton et al., 1995; Winterbottom, 2000), (Table S1). Early sources (1600–1840s) (e.g., estate maps, deposited plans, enclosure and tithe maps) have limited spatial coverage and accuracy, therefore they are not always suitable for assessing river planform adjustments at the catchment scale (Ferguson, 1977). The earliest maps with full continuous spatial coverage suitable for identifying planform adjustments at the catchment scale across England and Wales are the Ordnance Survey (OS) County Series maps (after 1840s) at a scale of 1:10,560 (Harley, 1975; Downward et al., 1994). Subsequent National Grid series and National Grid imperial and metric map editions (scale range 1:10,560–1:10,000), produced from large scale air photographs, provide a full coverage of England and Wales from the 1940s – 1990s (Table S1). Catchment and regional scale air photographs provide a recent (1940s - present) view of channel planform at a high resolution (i.e., 0.25 m) (Werritty and Ferguson, 1980; Petts et al., 1989). Air photographs and historic maps are geo-referenced in GIS for planimetric accuracy, following previous recommendations, using >8 hard-edged ground control points (GCPs) and a second order polynomial transformation (Hughes et al., 2006; Donovan et al., 2015; Donovan et al., 2019). Although scale differences and geo-referencing errors will exist between historic maps and air photographs, the datasets provide a valuable record of catchment scale 2D planform over a period of measurable change of approximately the last 150 yr.

2.2. Part 2: Characterisation of fluvial system and assessment of planform change

Channel planform adjustments and geomorphic variables are measured in two parts. Part 2A involves extracting geomorphic channel and catchment variables at station points (SPs) located along the channel network. The SPs are located at intervals scaled according to the stream order to reflect the natural scaling of channel width, valley bottom width, bar size, channel length and catchment area downstream (Leopold and Maddock, 1953; Strahler, 1957; Miller et al., 2002; Hughes et al., 2011). The SPs spacing interval is shorter for low stream orders, compared to high stream orders to account for the differences in channel size across a catchment. This approach differs to previous studies that have averaged river variables over length or extracted geomorphic variables at a fixed spacing interval and applied this to the entire channel network (Fryirs

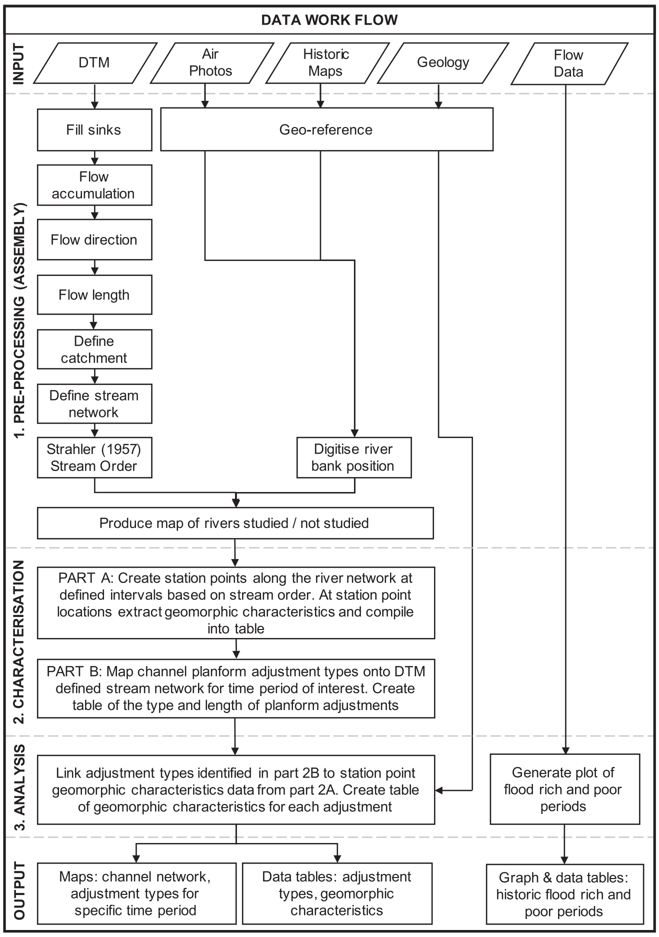


Fig. 1. Data requirements and GIS workflow for identifying and analysing planform adjustments, stable reaches and geomorphic variables. Part 1 involves manipulation of the DTM using GIS hydrology tools to identify the rivers and catchment typology. Part 2 involves identifying planform adjustments and extracting at-a-point channel and catchment geomorphic variables. Part 3 involves linking parts 2A and 2B together to understand the controls influencing the spatial and temporal pattern of planform adjustment. Part 2B and 3 are repeated for the different time periods of available historic maps and air photographs.

et al., 2009; Lisenby and Fryirs, 2016) (Fig. 2a). A fixed spacing interval can result in an unrepresentative sample where short, low stream order channels have only one SP to extract geomorphic variables, compared to longer higher stream order channels (Fig. 2).

The stream order channel network is labelled with a series of nodes (Fig. 2). Nodes are located at the start and end (tributary junction, or water body) of each channel. For each stream order, the first SP is located at the start node of the river. A point is then located at a user-defined distance (SP interval) downstream from the first point (e.g., 100 m); the next point is located at the stream order SP interval distance downstream from the last point and the pattern continues downstream. Where the distance from one SP to the last SP is less than the point spacing sampling increment, the measurement point is selected on the channel of interest upstream (i.e., of a junction or lake) where there are no significant lake or tributary backwater effects (Richards, 1982; Hey, 1979).

To select an appropriate SP interval, different spacing intervals can be tested. Assuming a minimum of two SPs on the shortest channel, a low-resolution SP spacing interval will have a long spacing interval (for example, 400 m for second order channels, 1000 m for fifth order channels). In contrast, a high resolution SP interval will have a short spacing interval (for example, 100 m for second order channels, 400 m for fifth order channels). Geomorphic characteristics can be extracted from the different SP intervals at different resolutions and analysis of covariance, ANOCOVA (Zar, 2010) can be used to identify statistical differences between the geomorphic variables of the different SP interval resolutions. If no statistical differences are present, the lowest resolution SP interval can be used to represent system geomorphic characteristics.

At each SP, the channel and catchment geomorphic variables (Table 1) are extracted and compiled into an attribute table (Fig. 1). These variables provide insight into reach and catchment scale morphology and sediment dynamics and can be directly extracted from the DTM, historic maps and air photographs (Martínez-Fernández et al., 2019; Bizzi et al., 2019). The key variables are defined as follows:

Channel length (m) is measured from the start of the stream order or junction node to the corresponding downstream end or junction node

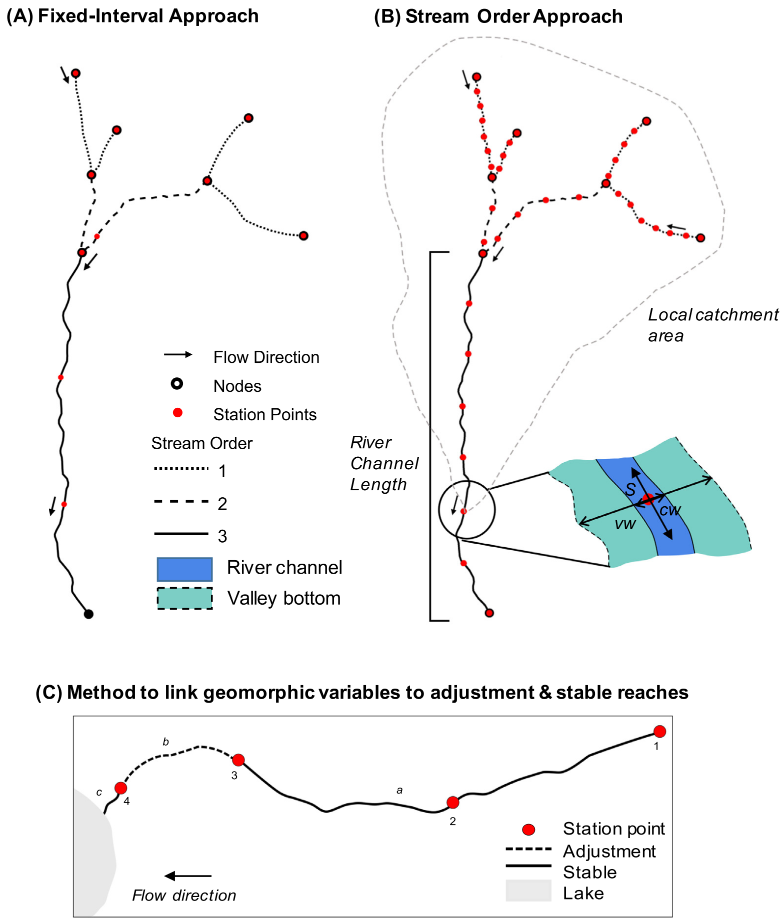


Fig. 2. Schematic of stream order channel start and end nodes and station point spacing intervals. (A) Example of 'fixed interval approach', a fixed SP interval distance often used on high order channels, applied to each stream order. (B) Example of SP intervals adjusted for each stream order and diagram of how geomorphic variables (*vw* = valley bottom width, *cw* = channel width, *S* = slope) are extracted in the methodology developed in this paper. (C) Diagram showing how SP variables are related to planform adjustments (method part 3). Continuous lines represent stable reaches (*a*, *c*), dashed lines indicate planform adjustments (*b*). Red dots indicate the SPs and the number indicates the station point ID. Stable reach *a* is represented by the mean characteristics at SPs 1, 2, 3. Planform adjustment *b* is represented by the mean characteristics of SPs 3 and 4. Stable reach *c* is assigned the characteristics of SP 4 as there are no downstream SPs due to the presence of the lake.

and represents the total channel length of the stream in that order (Fig. 2b). *Local channel slope (m/m)* is calculated at each SP. Elevation values are extracted from the DTM at intervals upstream and downstream of the SP that scale with each stream order (e.g., (stream order number – 1)*100)) to account for the variability in channel scale between the stream orders. *Local valley bottom width (m)* is measured at each SP, perpendicular to the channel banks and identified by breaks in slope along the distal edges of floodplains and terraces (Snyder and Kammer, 2008; Fryirs and Brierley, 2010). It defines the potential extent to which a channel can freely migrate laterally across the floodplain and therefore can define confined and unconfined channels (O'Brien et al., 2019). *Channel width* (m) is defined as the active channel width including bars and is measured at each SP perpendicularly from bank to bank (Wishart, 2004). *Bedrock* and *superficial geology* are categorical variables and are assigned locally to the observed river planform adjustments and stable reaches in part 3 of the method. *Local catchment area (km^2)* is defined as the upstream contributing area of a SP based on the surface topography from the DTM (Fig. 2b).

Based on the measured geomorphic variables secondary data can be calculated. For example, local catchment area is used to estimate discharge using a discharge-area power relationship (Knighton, 1999):

$$Q = a{\cdot}A^b \tag{1}$$

where A is the catchment area (km^2) and a and b are empirical coefficients derived from a power function fitted to area-discharge data. Many headwater catchments are ungauged, however, discharge data from gauging stations in a study region can be used to generate a regional catchment area-discharge relationship. For each gauging station within the study area flow return periods are calculated and plotted against their respective catchment areas to calculate regional a and b coefficients.

Table 1
Example of 1D and 2D geomorphic variables that can be extracted from historic maps, air photographs, geology maps and DTMs at different spatial scales, and the key processes they indicate (modified from Gurnell et al., 2016).

Spatial unit	Key process	Data variable
Region	Water balance	Climate data: precipitation (mm), discharge ($m^3 s^{-1}$)
	Sediment production	Geology
	Topographic conditioning (i.e., presence of mountains, lakes)	Topography derived from DTM
Catchment	Runoff production / retention	Climate data: precipitation (mm), discharge ($m^3 s^{-1}$)
	Sediment production	Geology
	Topographic conditioning (i.e., presence of mountains, lakes)	Topography derived from DTM
River	Channel network structure	Stream order and channel dimensions: catchment area (km^2), length (km), river channel slope (m/m)
	Flow and sediment regime (supply, transfer and deposition)	Discharge ($m^3 s^{-1}$), geology
Reach	Planform adjustments (sediment regime)	2D Planform adjustments identified from historical datasets Local slope (m/m), discharge ($m^3 s^{-1}$), channel width (m), unit (specific) stream power ($W m^{-2}$)
Geomorphic Unit	Sediment regime	2D adjustments to channel bars (i.e., bar area reduction, reorganisation or accretion) identified from historical datasets

Unit specific stream power ($W m^{-2}$) indicates river energy expenditure and the potential for sediment transfer and planform adjustment (Bagnold, 1966; Baker and Costa, 1987; Thompson and Croke, 2013; Marchi et al., 2016; Martínez-Fernández et al., 2019). Specific stream power is calculated using channel width and an area-discharge relationship (Eq. (1)) for a region or catchment (Bagnold, 1966; Baker and Costa, 1987):

$$\omega = \frac{\rho g Q S}{w} \quad (2)$$

where ω is the unit specific stream power ($W m^{-2}$), ρ is the density of water ($kg m^{-3}$), g is the acceleration of gravity ($m s^{-2}$), Q is the discharge ($m^3 s^{-1}$), S is channel bed slope (m/m) and w is the channel width (m). A return interval of 2 yr is commonly used for Q and ω calculations, which reflects the discharge that approximates bankfull conditions (Leopold and Wolman, 1957b; Dury, 1961; Hey, 1975; Harvey, 1977; Carling, 1988) and the potential for geomorphic work (Lisenby and Fryirs, 2016; Marchi et al., 2016).

Flood events prior to instrumental records can be identified from the analysis of historical documents (newspapers, historic accounts, etc.). Using historic and gauged flow data the cumulative number of flood events, following methodology of Pattison and Lane (2012), can be used to identify flood-rich and flood-poor periods and link to the timing and frequency of historic river planform adjustments.

Part 2B identifies the type of 2D planform adjustment along the river network over a given time interval. The type of adjustment (Fig. 3) is mapped as a polyline feature from the start to the end of the adjustment so that its location can be related to SP geomorphic variables and the length of the planform adjustment quantified. Reaches with no observed 2D planform adjustment are mapped as 2D stable indicating a balance of sediment input and output. However, it is important to note that these rivers might be adjusting vertically, which cannot be quantified in 2D analyses of historic maps and air photographs.

Fig. 3 demonstrates the types of channel planform adjustments identified in alluvial rivers (Hooke, 1977; Schumm, 1985; Fryirs et al., 2009; Lisenby and Fryirs, 2016). Planform adjustments are divided into four categories based on the characteristic scale of each adjustment. The four categories are not mutually exclusive and some adjustments may occur in combination, for example, bend adjustments are associated with the erosion of the outer riverbank and subsequent sediment deposition on the inside bend forming channel bars (Hickin, 1978; Richards, 1982).

Boundary adjustments are associated with an alteration to the channel planform where the channel: avulses across the floodplain, generating a new, secondary or multiple flow paths (Allen, 1965; Nanson and Knighton, 1996; Slingerland and Smith, 2004), switches from multiple flow paths to a single flow path (Passmore et al., 1993), or is shortened via cut offs causing channel straightening/realignment. Boundary adjustments can take place at the reach scale (i.e., cut off), or affect the entire channel length (i.e., avulsion) (Slingerland and Smith, 2004). They typically occur over a short time period (<1 yr), often during a flood event (Jones and Schumm, 1999), although they can also be progressive, occurring in response to continued erosion and deposition of sediment (Stouthamer and Berendsen, 2001).

In contrast, channel width adjustments affect shorter lengths of river channel. Here, width adjustments are defined where there is a major change (>50%) in the channel width to avoid misrepresentation of minor width adjustments caused by image scale-related effects. Bend adjustments can occur via extension, expansion, translation enlargement, rotation or complex change (Hooke, 1977; Fryirs et al., 2009) (Fig. 3). Bend and width adjustments can be progressive adjustments or occur in response to a flood event. The development of bars in the channel can cause width, bend or boundary adjustments or can be a response to these adjustments (Fig. 3) (Leopold and Wolman, 1957a). The pattern and rate of bar adjustments can be a useful indicator of the stability of river channels (Church and Jones, 1982). Bar adjustments can occur over short temporal scales, in response to an event (i.e., flood, valley landslide) or be present in the channel for ~100 yr (Jackson, 1975; Church and Rice, 2009). Bar adjustments are considered to be more stable forms of adjustment inherent within the system when they occur singularly (e.g., not in combination with another adjustment), compared to boundary or major width adjustments that involve a change to the position and 2D form of the channel on the valley floor (Brierley and Fryirs, 2005b; Fryirs and Brierley, 2012).

The types of 2D planform adjustment outlined in Fig. 3 are readily identified by comparing historic maps and air photographs. Therefore, geo-referencing errors between historic maps and air photographs are unlikely to significantly affect the categorisation of the adjustment type or adjustment length.

2.3. Part 3: Analysis: linking planform adjustments and geomorphic variables

The main outputs of Part 2 include: (a) channel and catchment geomorphic variables at station points along the channel network, and (b) 2D channel planform adjustment types and stability as polyline features along the channel network for each time period. Part 3 combines parts 2A and 2B to develop an understanding of the key geomorphic variables influencing the types of planform adjustment and stability.

To link SP variables to adjustment and stable reaches the geomorphic variables of the SP upstream and downstream of the adjustment or inactive reaches are averaged (Fig. 2c). For example, in Fig. 2c adjustment *b* is assigned the mean geomorphic variables of SP 3 and 4. If an

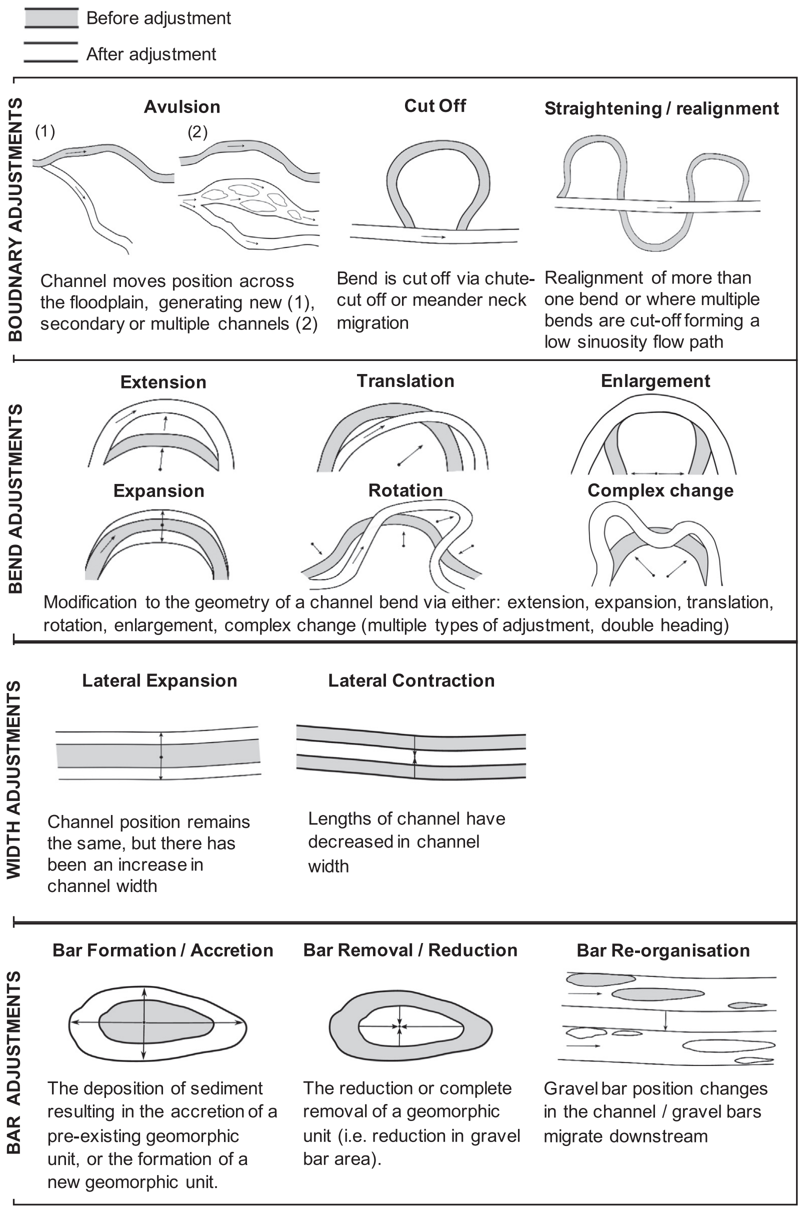


Fig. 3. Schematic of planform adjustment types and definitions adapted from Brierley and Fryirs (2005a, 2005b) and Fryirs et al. (2009).

adjustment or stable reach extends or lies between two or more SPs then the average geomorphic variables are taken from all of the respective SPs (Fig. 2c). If an adjustment extends over the junction between two stream orders (i.e., at tributary junctions), the mean geomorphic characteristic variables are taken from the upstream SP and downstream SP. If the adjustment occurs downstream of the last SP (i.e., upstream of a lake or waterbody) it is assigned the variables of the last closest SP.

3. Case study

3.1. Part 1: Selection of region, assembly and pre-processing of data

To test this approach, the methodology is applied to the Wasdale Catchment (45 km^2, Fig. 4) in the Lake District, northwest England. This upland catchment is strongly influenced by the geology, glacial history and climate with a dynamic fluvial system (Harvey, 1997). The present river planform consists of straight low sinuosity first and second order erosional bedrock channels, e.g., Piers Gill and Gable Beck (Fig. 4). Downstream, depositional features dominate, and channels are unconfined with wandering and braided planforms in the third, fourth and fifth stream orders (Fig. 4C) (Harvey, 1997). A small debris cone is present where Gable Beck joins Lingmell Beck and there is a large fan delta where Mosedale and Lingmell Becks empty into the head of Wast Water, which adjoins an alluvial fan of Lingmell Gill (Harvey, 1997).

The bedrock geology of the area consists of Ordovician Borrowdale Volcanic Group rocks (Wilson, 2005). The superficial geology consists of primarily fluvial deposits in the lower reaches of Mosedale Beck, Lingmell Beck and Lingmell Gill (Fig. 4C). Glacigenic deposits (Devensian till, diamicton) are found in the upper reaches and headwaters of the river channels (Fig. 4). River channel sediments are generally coarse, typically boulder gravels in the upper reaches fining to cobble gravels downstream (Skinner and Haycock, 2004). Little evidence of anthropogenic modification exists in the low order channels in the headwaters of the Wasdale catchment (Skinner and Haycock, 2004). In contrast, evidence of straightening, embankments and walled riverbanks are present along the lower reaches of Lingmell Beck and Mosedale Beck (Skinner and Haycock, 2004). Mosedale Beck and Lingmell Beck are high energy systems and planform adjustments are expected despite the anthropogenic modifications (Skinner and Haycock, 2004).

Historic maps and air photographs with full coverage of the Wasdale catchment are available from 1860s – 2010. Historic OS maps include the years: 1867–68 (1:10,560); 1956–57 (1:10,560); 1974–1980 (1:10,000); and air photographs: 1995 (Natural England, 0.25 m resolution), 2003–04 and 2009–10 (source: © Bluesky International Ltd., 25 cm resolution), (Table S1). Air photographs and historic maps were georeferenced in Esri ArcMap GIS to an OS base map in British National Grid coordinates. Error was assessed using the root-mean square error (RMSE) of the GCPs as well as in 14 independent test points (local error) (Hughes et al., 2006). A decrease in RMSE and test point error was observed between the 1860s map (RMSE = 2.6 m, test point error = 3.7 ± 2 m) and 2010 air photograph (RMSE = 0.8 m, test point error = 1.4 ± 1.4 m) (Table S3). A contemporary 5 m DTM (Digimap, 2017) was used to define the baseline stream order network in GIS.

3.2. Part 2: Characterisation of fluvial system and assessment of planform evolution

Planform adjustments were mapped: (1) over the ‘full period’, by comparing the oldest available map (1860s) of river planform to the most recent (2010) full coverage air photograph, and (2) at higher frequency intervals using intermediate dated historic maps and air photos during the full period (‘intermediate periods’) (Table S1). Planform adjustments were mapped on second, third, fourth and fifth order channels. First order channels were not mapped as the resolution of air photographs and historic maps meant the channels <1 m wide could not easily be identified. First order channels are often topographically confined in headwater catchments, with entrenched channels or

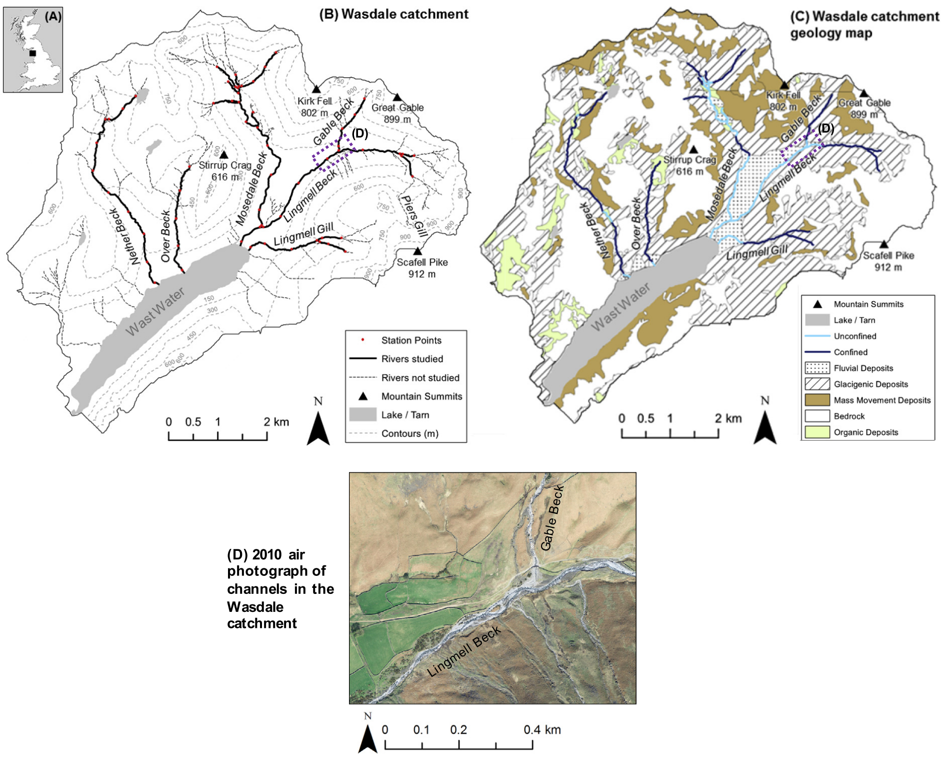


Fig. 4. (A) Location of Lake District upland region, north-west England. (B) Wasdale catchment study area (45.4 km^2) and channel network. Rivers not studied include those that are not identifiable from historic maps and air photographs (mainly first order channels). (C) Geology map of the Wasdale catchment showing the superficial geology (source: BGS, 2016), and rivers studied that are topographically confined or unconfined. (D) Example of 2010 air photograph (Digimap, 2017) of channels in the Wasdale catchment. Area of air photograph is indicated by dashed purple box in Fig. 4B and C.

narrow valleys and therefore we expect to see minimal 2D lateral planform adjustment in these channels over the period of measured change. However, it is important to recognise that first order channels can adjust vertically and supply sediment to the downstream channel network.

The SPs in the Wasdale catchment (Fig. 4) were located at 400 m, 600 m, 800 m, and 1000 m intervals for second, third, fourth, and fifth order channels, respectively. The spacing point interval was determined based on analysis of three station point interval resolutions (Table S2, Fig. S1). No statistical differences were observed between the three SP interval resolutions at the 95% confidence level after ANOCOVA (Zar, 2010), therefore, we assumed that geomorphic variables extracted at the lowest resolution SP interval (Table S2, Fig. S1) are representative of the geomorphic variables for each stream order. Elevation values to calculate channel slope were extracted 100 m, 200 m, 300 m and 400 m upstream and downstream of the SPs for second, third, fourth and fifth order channels, respectively (Table S3, Fig. S2). The intervals used to extract elevation values coincide with a similar range of previously used intervals (Alber and Piégay, 2011; Bizzi and Lerner, 2012; Lisenby and Fryirs, 2016; Martínez-Fernández et al., 2019).

No discharge gauging stations are located in the Wasdale catchment, so to calculate stream power flow data is combined from 19 flow gauges across the Lake District upland region to produce a regional area-discharge relationship (Eq. (2)) (Fig. S3). The 19 flow gauges chosen have a minimum record length of 30 yr and capture a range of catchment sizes (18–363 km^2). Only three flow gauges occur upstream of lakes, therefore, when using the gauges downstream of lakes it is assumed that the lakes are full during bankfull flow (flood) conditions. Values of unit stream power are calculated for the 2 yr return interval flow as this is representative of bankfull discharge in gravel-bed rivers in similar upland settings (Leopold and Wolman, 1957b; Hey, 1975; Harvey, 1977; Carling, 1988; Harvey, 2001).

To understand the temporal pattern of planform adjustments and the role of flood events during the 150 yr time period, gauged flow data is linked to longer term events identified using historical descriptions of major geomorphological events (i.e., landslides, changes of stream course, or large scale damage to buildings etc.) (Watkins and Whyte, 2008). Extreme flood events in the gauged data were identified by using the peak-over-threshold (POT) approach (Robson and Reed, 1999). Previous studies have defined unique POT discharge values for a catchment (i.e., Rumsby and Macklin, 1994; Pattison and Lane, 2012). However, because we are comparing peak events across 19 gauges, a single discharge value is not representative of the range of catchment sizes. Instead, we set a high POT of 75% of the gauged flow record. This threshold means only the largest flood events are used so the dataset includes an average of 1 flood event per year across the gauged records (Robson and Reed, 1999). To reduce bias in any catchment-specific flood events identified in the gauge records, we remove peak events that are not observed across >50% of the 19 flow gauges. The cumulative number of flood events in the historical and gauged record is plotted over time to generate an overview of flood-rich and flood-poor periods across the Lake District upland region.

4. Results

4.1. Characterisation of the fluvial system

In total, 18 channels (total length = 24 km) were studied in the Wasdale catchment, with a total of 63 SPs. There were eight second order channels, seven third order channels, two fourth order channels and one fifth order channel. The stream orders differ in length, steepness, confinement (valley bottom width) and specific stream power reflecting the longitudinal variation in the upland headwater channels (Fig. 5). Local mean channel slope decreases from 0.2 ± 0.09 to 0.004 ± 0.002 from second to fifth order channels (Fig. 5). Channel width increases by a factor of four downstream through the stream order network; second order channels have the narrowest mean channel widths (4 ± 2 m) and fourth and fifth order channels have the largest mean channels widths (16 ± 1 m). Catchment area similarly increases from second order channels (mean catchment area = 0.8 ± 0.4 km^2) to fifth order channels (19 ± 1.5 km^2) (Fig. 5). Mean valley bottom width increases by a factor of 18 downstream from 31 ± 43 m in second order channels to 550 ± 30 m in fifth order channels (Fig. 5). Mean bankfull stream power decreases by a factor of 25 downstream from 620 ± 305 W m^{-2} in second order channels to 25 ± 8 W m^{-2} in fifth order channels (Fig. 5).

4.2. Planform adjustments

Planform adjustments in the Wasdale catchment are assessed (1) over the ‘full period’ by comparing the earliest historic map and recent air photograph, 1860s - 2010 (150 yr); and (2) at ‘intermediate periods’ at higher frequency intervals (1860s–1950s; 1950s–1980; 1980–1995; 1995–2004; 2004–2010) during the 150 yr period.

4.2.1. Full period (1860s – 2010) results

Over the full period, 114 planform adjustments were identified (Fig. 6A). The total length of channels mapped as stable was 68% (16 km) and adjusting was 32% (8 km). Bar adjustments were the most common forms of adjustment (n = 68, 60%, Fig. 6A) and affected an average of 9% of the channel length (Fig. 7B). The mean percentage of channel length affected by bend adjustments (n = 19, 17%) was 6%; boundary adjustments (n = 12, 11%) was 17% and width adjustments (n = 15, 13%) was 11% (Fig. 7). The highest frequency of planform adjustments occurred in third order (n = 45, 40%) and fourth order (n = 48, 42%) channels (Fig. 6A) where catchment area increases and channels become topographically unconfined (Fig. 5). The 2D stable reaches (n = 66) affected an average of 20% of the channel length over the full period (Fig. 8).

Over the full period of analysis, 43 of the mapped planform adjustments (38% of the total number of adjustments) occurred in combination with another planform adjustment type. Thirty percent of the total combined planform adjustments were bar and width adjustments, 28% were bar and bend adjustments, 28% were bar and boundary adjustments, 5% were boundary and width adjustments, and 9% were bar, boundary and width adjustment combinations.

4.2.2. Intermediate period results

In the shorter time interval comparisons, bar adjustments were the most frequent planform adjustment observed (1980–1995, n = 56; 1995–2004, n = 86; 2004–2010, n = 178) (Fig. 6). Boundary adjustments were observed in the 1860s – 1950s, and 1950s – 1980 intermediate time periods, however, these adjustments were absent after the 1980 period (Fig. 6).

A reduction in the mean percentage of channel length affected by planform adjustments is observed over the stream order network in the intermediate time periods (Fig. 7). Planform adjustments in 1860–1950s and 1950s–1980 affected an average of 40% of the channel length, whereas adjustments over the shorter time span intervals from 1980–1995, 1995–2004 and 2004–2010 affected an average of 22–13% of the channel length (Fig. 7). This coincides with a reduction of the occurrence of boundary adjustments from 1980 to 2010, which affected a mean of 17% of the river channel length from 1860s – 1980 (Figs. 6 and 7).

Second order channels have the highest mean percentage of length categorised as 2D stable over 1860s – 1950s (100%), 1980–1995 (47%) and 1995–2004 (35%) (Fig. 8). Over the period of analysis there has been a progressive reduction in the overall length of channel mapped as stable (Fig. 8), this is likely caused by an increase in the frequency of bar adjustments being mapped from 1980s onwards as a result of the changing resolution and type of data source used.

Combined planform adjustments were identified in all of the intermediate time periods. From 1860s–1950s, 33% (n = 15); 1950s–1980, 24% (n = 16); 1980–1995, 25% (n = 18); 1995–2004, 18% (n = 18) 2004–2010, 8% (n = 15) of river planform adjustments were

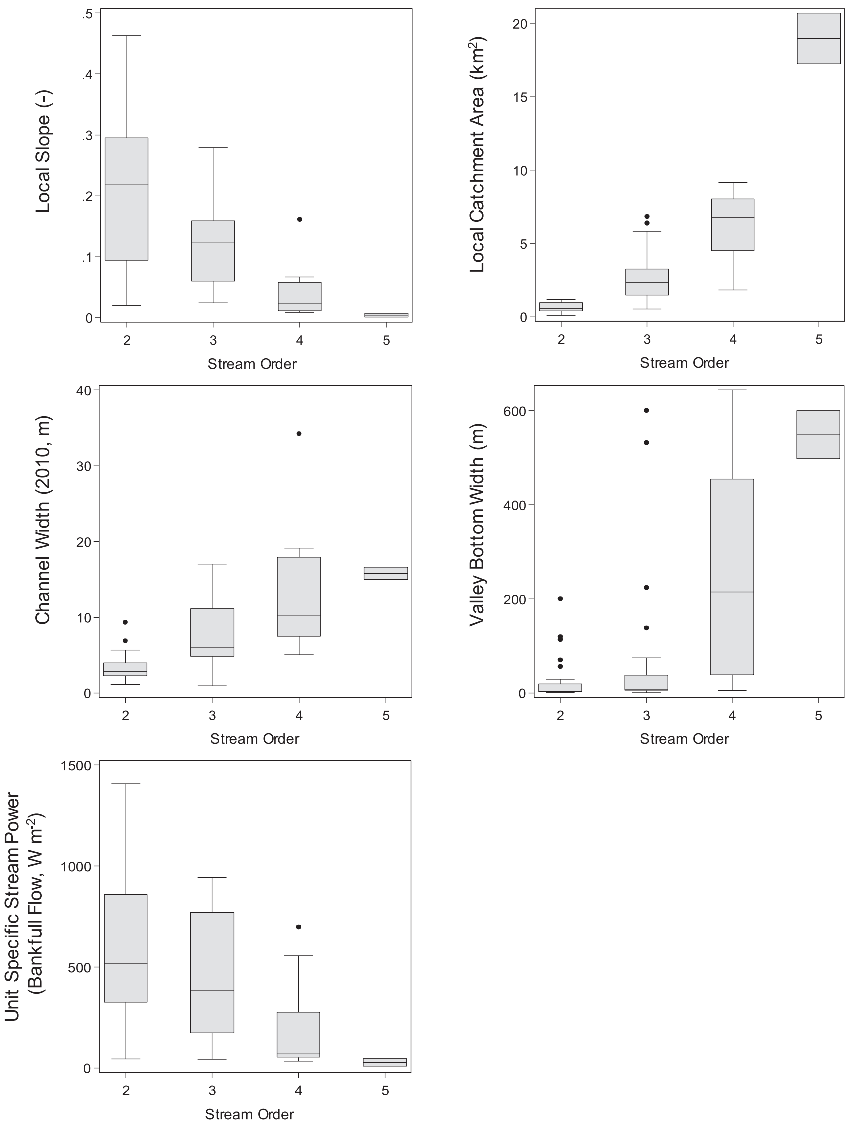


Fig. 5. Box plots showing the slope, catchment area, valley bottom width and unit specific stream power characteristics extracted from the station points for each stream order in the Wasdale catchment. Statistically significant differences were identified between the mean of the geomorphic variables between each stream order at the 95% confidence level.

overlapping. The most frequently combined planform adjustments during the intermediate periods were bend and bar adjustments ($n = 35$).

4.3. Geomorphic variables of planform adjustment and stable reaches

To identify the key geomorphic characteristics influencing the location and extent of planform adjustments, a comparison was made between the geomorphic variables extracted from the SPs and the planform adjustment and stable reach data for all time periods (full period and intermediate periods) (Fig. 9). In total, 1048 2D adjustment and stable reaches were compared, of this frequency: bar adjustments accounted for 42% ($n = 438$); bend adjustments 7% ($n = 70$); boundary adjustments 3% ($n = 27$); width adjustments 5% ($n = 49$); and the frequency of stable reaches was 44% ($n = 464$).

Stable reaches were found to have differences between planform adjustment mean geomorphic variables over the full data set (Table 2). Stable reaches ($n = 464$) had a mean channel width of 8 ± 5 m, slope of 0.1 ± 0.08, local catchment area of 3.4 ± 3.3 km^2, valley bottom width of 110 ± 157 m and bankfull unit stream power of 424 ± 260 W m^{-2} (Fig. 9). The 2D stable reaches were most commonly found in confined second order channels, where bend and boundary adjustments are less likely because of limited

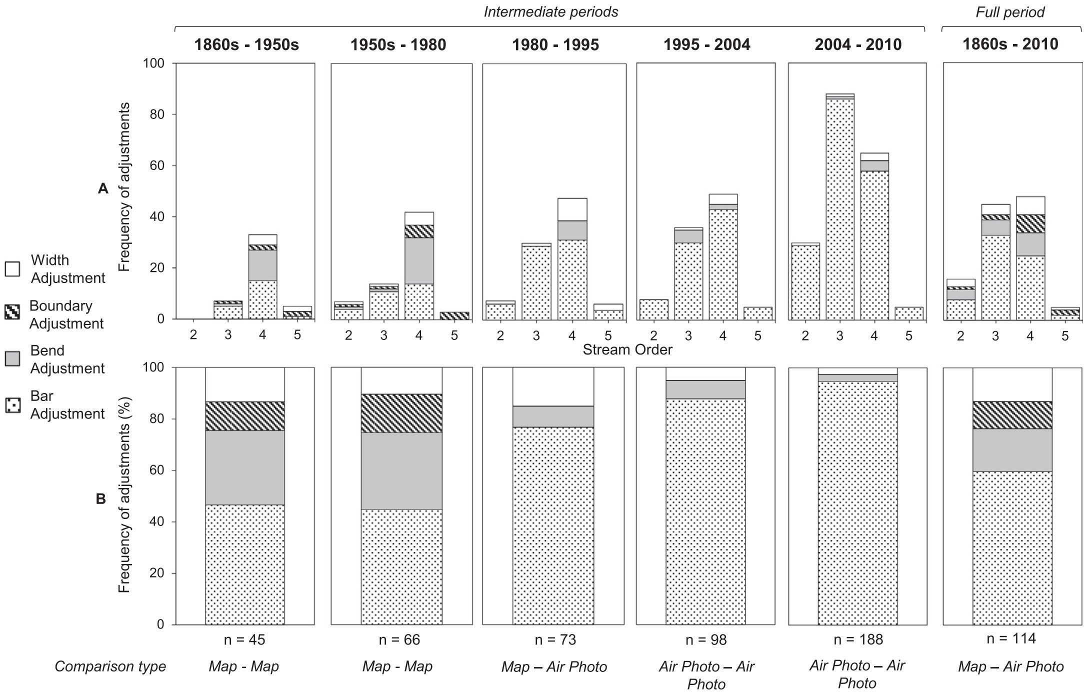


Fig. 6. (A) Frequency of planform adjustments by stream order, and (B) percentage frequency of planform adjustments in the Wasdale catchment, UK, for the available historical maps and air photographs (1860s – 2010).

space for lateral adjustment (Fig. 9). Adjustment reaches ($n = 584$) had a mean channel width of 11 ± 5.6 m, slope of 0.08 ± 0.07, local catchment area of 4.7 ± 4.1 km^2, valley bottom width of 170 ± 194 m and bankfull unit stream power of 325 ± 250 W m^{-2} (Fig. 9). Boundary adjustments occurred in unconfined valley reaches, where mean valley bottom width is 430 ± 165 m, mean slopes are 0.04 ± 0.06, and where there is a large mean upstream catchment area of 9.4 ± 6 km^2 (Fig. 9). In contrast, bar adjustments were less restricted to unconfined valleys and low slopes, occurring on mean valley bottom widths of 145 ± 180 m and where mean slopes were 0.09 ± 0.08.

A one-way ANOVA and Tukey (HSD) was performed to identify if a statistically significant difference between the mean geomorphic variables and the adjustment and stable reaches for each stream order was present (Table 2). The fifth order channel was truncated by Wast Water and was excluded from the statistical analysis because of its short 590 m length and the small number of observed adjustments (38, 4% of total of adjustments studied), therefore, results focus on the ANOVA analysis of planform data for second, third and fourth channels.

Third and fourth order channels display the highest number of significant differences (n^*) ($n^* = 22$) between adjustment types and the geomorphic variables (Table 2) compared to second order channels ($n^* = 5$). Second order channels have steeper channel slopes and higher unit stream power values (Fig. 5), however, they are characterised by a narrower range of values for catchment area (0.2–1.7 km^2), channel width (2–12 m) and valley bottom width (2–210 m) compared to third and fourth order channels (Fig. 5). In confined, second order channels the space available for channel adjustment is restricted and therefore there are fewer significant differences between the geomorphic variables and adjustment types ($n^* = 5$) (Table 2).

In contrast, the geomorphic variables (catchment area, valley bottom width, channel width) increase in third and fourth order channels (Fig. 5) and display the highest number of statistically significant differences ($n^* = 22$) between adjustment types and the geomorphic variables (Table 2). The highest number of statistical differences identified in third and fourth order channel planform adjustments are associated with valley bottom width ($n^* = 9$) (Table 2).

The highest number of significant differences between geomorphic variables and planform adjustments were between bar and boundary adjustments ($n^* = 7$), and boundary and width adjustments ($n^* = 5$) in third and fourth order channels (Table 2). Bar adjustments in third and fourth order channels occurred where mean valley bottom width was 145 ± 170 m, boundary adjustments occurred where the mean valley bottom width was 430 ± 140 m and width adjustments occurred where the mean valley bottom width was 240 ± 220 m. Boundary adjustment frequency was lower in second order channels because topographic confinement limits lateral adjustment (Fig. 4C). The lowest number of significant differences in second, third and fourth order channels identified were between bend and bar adjustments ($n^* = 1$) and bar and width adjustments ($n^* = 1$); these adjustments often occurred in combination. The combined data column (Table 2) suggest significant differences were observed between most geomorphic variables, but the highest number of statistical differences could be identified by differences in channel width and valley bottom width ($n^* = 8$); these statistical differences are concentrated in third and fourth order channels.

4.4. Flood-rich and flood-poor periods and the timing of planform adjustments

To understand the temporal pattern of channel planform adjustments, we use archival and flow gauge information to identify flood-rich and flood-poor periods (Fig. 10A). We identified five flood-rich periods across the Lake District upland region that

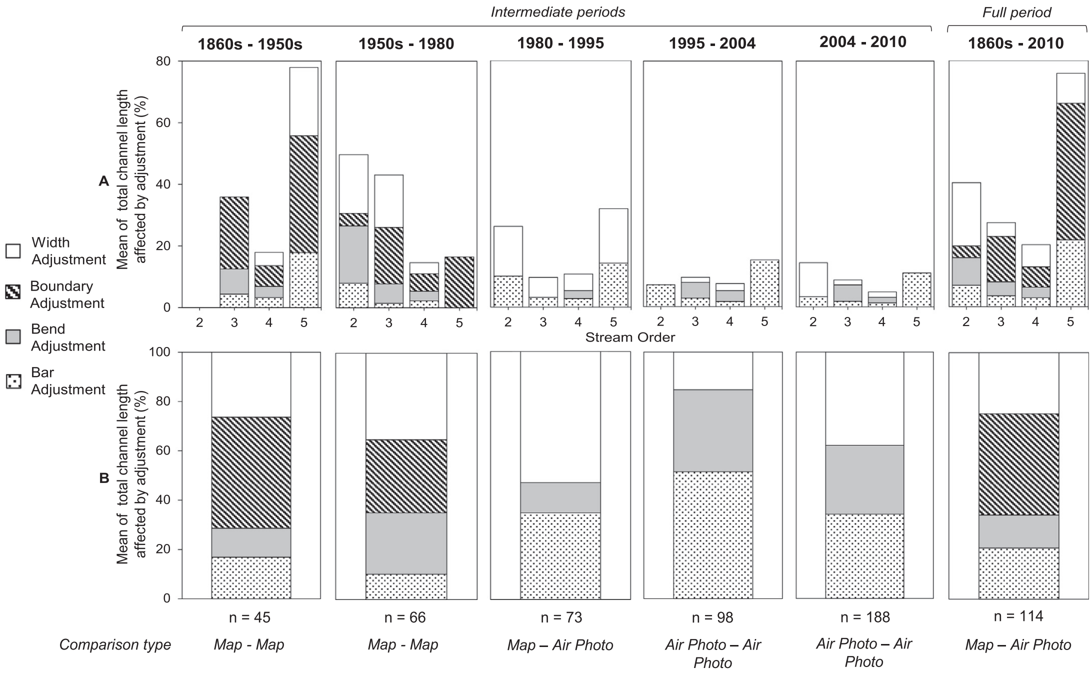


Fig. 7. Mean percentage of channel length affected by planform adjustment by stream order (A) and mean percentage of channel length affected by planform adjustment (B) in the Wasdale Catchment, UK, for the available historical maps and air photographs (1860s – 2010).

correspond to previously reported flood-rich periods in northern UK and northwestern Europe (Macklin and Lewin, 1998; Pattison and Lane, 2012; Macdonald and Sangster, 2017) (Fig. 10A). Fig. 10A shows the regional pattern of flood-rich and flood-poor periods from 19 flow gauges in the Lake District, however, individual catchments can be affected by local flood conditions. For example, Johnson and Warburton (2002) reconstructed local historic flood events using lichenometry in Raise Beck (NGR NY 330118, central Lake District, ~ 15 km northeast of the Wasdale catchment) (Fig. 10A). Three of the Raise Beck flood events coincide with the regional flood-rich periods and three do not, highlighting local variability in flood conditions (Fig. 10A). Because there are no flow records in the Wasdale catchment we can only use regional flood data, but acknowledge there will likely be local differences in flood histories between valleys.

Fig. 10B shows the average length of planform adjustments types for each time period. Boundary adjustments were not observed after the 1980s (Fig. 10B). The average length of channel affected by bend and bar adjustments has been relatively consistent over all time periods (Fig. 10B). Width adjustments affected a

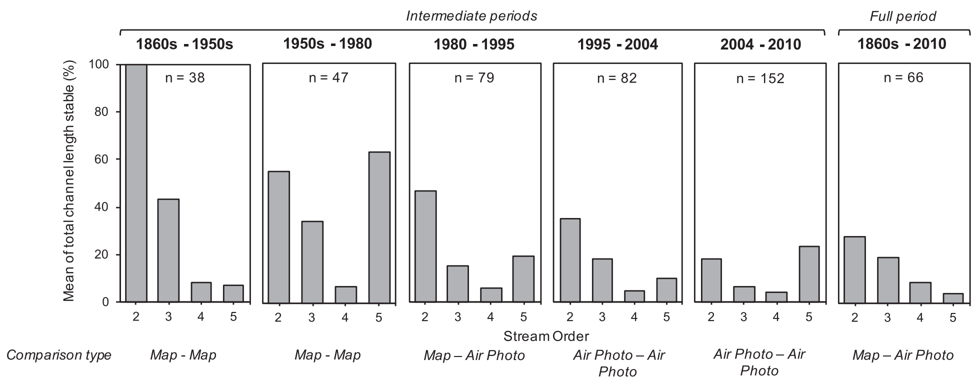


Fig. 8. Mean percentage length of stable reaches for each time period plotted against stream order for the Wasdale catchment, UK.

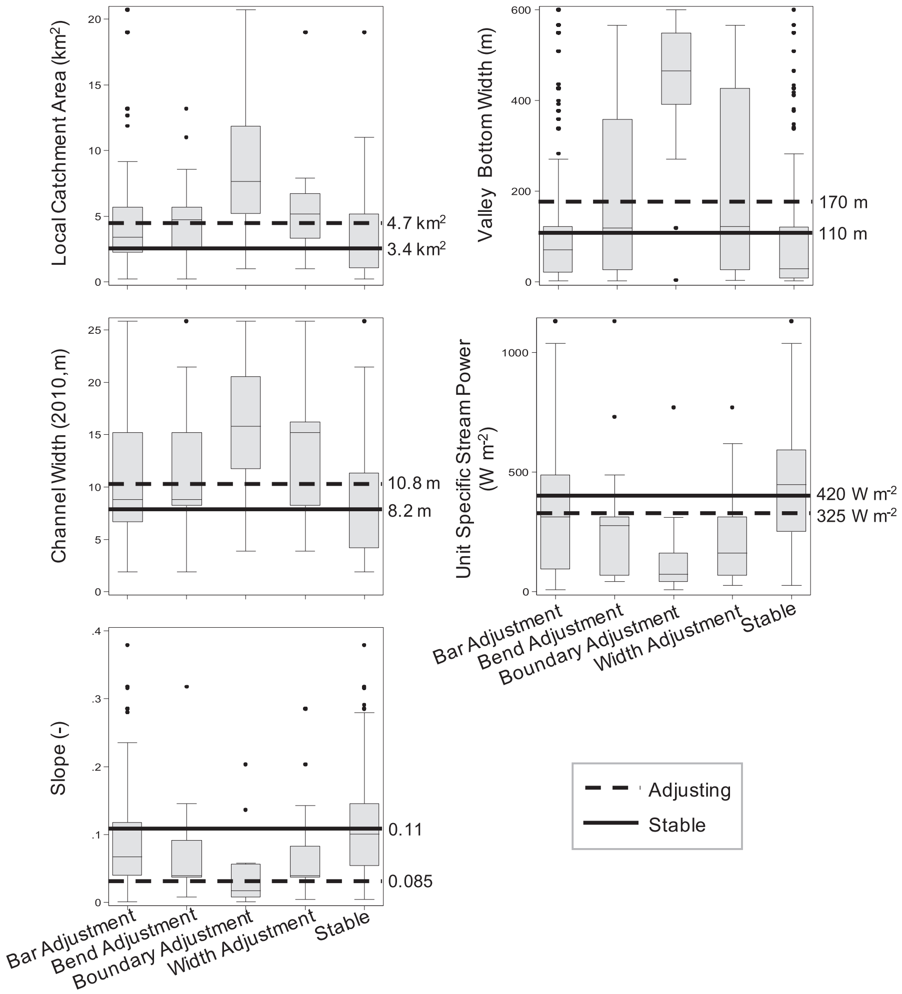


Fig. 9. Box plots showing the geomorphic variables for each planform adjustment category for all time periods. Continuous lines represent the mean geomorphic value for stable reaches, dashed lines indicate the mean geomorphic values for adjusting reaches.

greater length of channel planform in 1860s–1950s, 1950s–1980 and 1980–1995 time periods (Fig. 10B). The mean percentage length of stable reaches over time decreased (Fig. 10B). The changing resolution of the map and air photographs, and the length of sampling interval over which planform adjustments are mapped, will influence the type and frequency of adjustments identified. For example, air photograph resolution (0.25 m) will enable smaller adjustments to be identified (i.e., bar adjustments),

Table 2
One-way ANOVA and Tukey (HSD) results showing statistically significant differences (at 95% confidence interval p value <.05), between planform adjustments, stable reaches, geomorphic variables and stream order. Dots indicate the presence of a statistically different relationship. S is local slope (m/m), A is local catchment area (km^2), W is channel width (2010, m), VW is valley bottom width (m), ω is the 2 yr Return Interval Specific Stream Power (W m^{-2}). Combined column represents analysis for all stream orders, green highlighted columns shows the geomorphic variables with the highest number of statistically significant differences.

Comparison between adjustment categories	Stream Order 2					Stream Order 3					Stream Order 4					Combined				
	S	*A*	*W*	*VW*	*ω*	*S*	*A*	*W*	*VW*	*ω*	*S*	*A*	*W*	*VW*	*ω*	*S*	*A*	*W*	*VW*	*ω*
ρ value	0.008	0.111	0.003	0.441	0.056	0.114	0.342	0.000	0.000	0.010	0.015	0.000	0.008	0.000	0.076	0.000	0.000	0.000	0.000	0.000
Bar Adjustment vs Bend Adjustment	•															•		•		•
Bar Adjustment vs Boundary Adjustment								•	•		•	•	•	•	•	•	•	•	•	•
Bar Adjustment vs Width Adjustment	•															•	•	•	•	•
Bar Adjustment vs Stable			•					•	•								•	•	•	•
Bend Adjustment vs Width Adjustment								•	•			•		•			•	•	•	
Bend Adjustment vs Boundary Adjustment																•		•	•	•
Bend Adjustment vs Stable			•																	
Boundary Adjustment vs Width Adjustment								•	•			•	•	•		•	•	•	•	•
Boundary Adjustment vs Stable												•		•			•		•	
Width Adjustment vs Stable			•					•	•							•	•	•	•	•

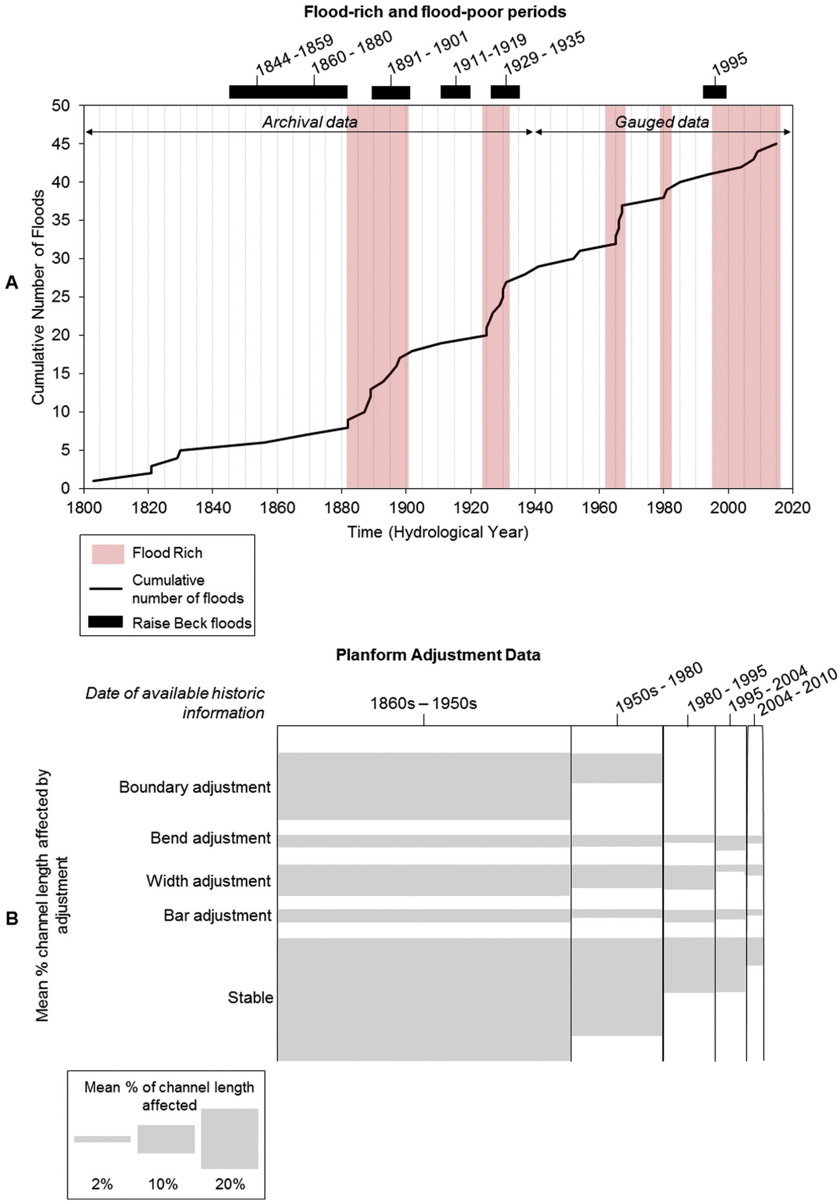


Fig. 10. (A) Cumulative number of high flow events as a function of time for the Lake District upland region. Peak flow data is based on documented extreme flood events from archival evidence and gauged data (19 gauges) that represent POT flows. Where the gradient of the line is steep it indicates a high frequency of large flood events and flood-rich periods (red bars). A local flood record at Raise Beck (NY 330118) from Johnson and Warburton (2002) is plotted against the regional flood record. (B) Mean length of channel affected by planform adjustment (%) (height of grey bars is proportional) for each time period map / air photograph comparison. Grey bar length represents the time span between available map/photo comparisons.

reducing the length of channel categorised as 2D stable (Fig. 6). Similarly, the length of historic map and air photograph sampling interval decreases towards the present, which will impact the number of recorded channel adjustments depending on whether a flood-rich period falls between two observational epochs or not. Despite these limitations, this is the best available catchment scale data of 2D planform adjustments, stable reaches and historic flood events over the 150 yr time period.

5. Discussion

5.1. Catchment scale patterns and controls of 2D planform adjustment

In this paper, a systematic methodology to quantify historic 2D channel planform adjustments, stable reaches and the associated geomorphic variables at the catchment scale has been developed and applied. Previous river planform adjustment studies have emphasised the dynamic nature of upland river channels (Newson, 1989). In the Wasdale catchment, a similar picture emerges with 32% of the total channel network length classified as adjusting between 1860s-2010 (Fig. 11). Similar patterns of actively adjusting reaches have been identified in British rivers using historical sources (Ferguson, 1981). For example, Lewin et al. (1977) identified that 25% of 100 randomly surveyed channel reaches in Wales were adjusting over a period of 44–78 yr. Hooke and Redmond (1989a) estimated that over an 89 yr period (1870–1959), 35% of UK upland rivers experienced planform adjustment.

The structure of a catchment, primarily determined by the geological and glacial history, plays an important role in influencing sediment continuity and patterns of planform adjustment (Milne, 1983; Downs and Gregory, 1993; Thomas, 2001; Sear and Newson, 2003; Fryirs et al., 2009). In headwater catchments, low order channels are often topographically confined (Milne, 1983; Montgomery and Buffington, 1993; Downs and Gregory, 1993) and have been termed 'resistant' or 'insensitive' to planform adjustments (Brunsden and Thornes, 1979; Sear et al., 2003; Fryirs et al., 2009; Thoms et al., 2018; Piégay et al., 2018; Fuller et al., 2019). In the Wasdale case study, second order channels were topographically confined (mean valley bottom widths of 31 ± 43 m, Fig. 5) and bar adjustments were the most frequent form of adjustment (Fig. 6). The presence of bar adjustments can indicate the channels are locally active in terms of sediment supply and transfer, and therefore show little change to the channel boundaries over time (Fig. 6). One exception to this general result was observed in Gable Beck, a second order channel, where a local cut off and width adjustment (1950s – 1980) occurred where valley bottom width expands and a small debris cone is present, allowing the channel to become locally unconfined (Figs. 4C and 11). Overall, however, topographically confined low order channels displayed patterns of persistent 2D stability, indicating a high level of sediment continuity and relative balance between sediment input and output.

In contrast, downstream in high order channels in the floodplain valley transfer zone, valley bottom width increases markedly (Fig. 5) creating space (Schumm, 1977; Church, 1996) for the channel to interact with floodplains laterally (Ibisate et al., 2011). The highest frequency of planform adjustments was observed in third to fifth order channels (Fig. 6). The most active adjustment locations were observed in the downstream reaches of Lingmell Beck (fourth and fifth order channels) where mean valley bottom width was 410 ± 110 m, allowing room for lateral planform adjustments. Lingmell Beck also had a low mean channel slope 0.03 ± 0.01, large mean catchment area 12 ± 1.7 km^2, and low mean stream power 130 ± 80 W m^{-2} (Fig. 5). Unconfined reaches with low specific stream powers can accommodate sediment deposition (Knighton, 1999; Reinfelds et al., 2004; Lea and Legleiter, 2016), which can lead to local aggradation (poor sediment continuity) and super-elevation of the bed in relation to the floodplains, which can instigate larger scale adjustments such as avulsions (Jones and Schumm, 1999). This is evidenced by large depositional areas in the mid to lower reaches of Lingmell Beck (Skinner and Haycock, 2004).

McEwen (1994) similarly identifies changes in river channel planform stability along the River Coe, Scotland. In the upstream reaches, the River Coe is relatively confined and stable, however, downstream the channel floodplain valley, slope and stream power changes, and the channel planform transitions to a wandering gravel-bed river where the channel actively reworks the floodplains and sediment aggrades in the channel (McEwen, 1994). The floodplain valley transfer zone represents an important sediment source and store regulating sediment continuity downstream over different timescales (Werritty and Ferguson, 1980; Ferguson, 1981). Joyce et al. (2018) highlight the importance of valley floodplains in storing sediment during extreme flood events causing sediment attenuation at the channel outlet. In the Wasdale catchment, persistent adjustment reaches over the last 150 yr indicate locations of continual sediment erosion and deposition in the floodplain valley transfer zone. For example, where the channel becomes unconfined in the mid to lower reaches of Lingmell Beck, repeated bar, bend and width adjustments were recorded in the intermediate periods of analysis (Fig. 11) and are evidenced by depositional features (Skinner and Haycock, 2004). Sediment continuity can therefore be both discontinuous at the event scale and over much longer timescales of measurable change (150 yr).

The statistical analysis investigated the importance of the different types of river planform adjustment in relation to catchment geomorphic variables (Table 2, Fig. 9). Valley bottom width and channel width could be used to identify differences in stable reaches, bend, boundary, width and bar adjustments across the catchment (Table 2). However, the analysis highlighted that not one geomorphic variable alone could be used to define a particular type of river planform adjustment. This is because planform adjustments occur in response to interactions of multiple geomorphic variables. Second, it is difficult to identify the geomorphic variables of individual planform adjustment categories because planform adjustments can occur in combination. Fig. 12 summarises the frequency of interactions between planform adjustment categories in the Wasdale catchment. In the full-time period analysis (1860s – 2010), 38% ($n = 43$) of river channel planform adjustments identified were coincident with another planform adjustment. Bar adjustments are the most frequent type of adjustment and are associated equally with channel boundary, width and bend adjustments (Fig. 12). This result is to be expected given that the bar can be regarded as the fundamental geomorphic unit in fluvial systems (Church and Rice, 2009; Rice et al., 2009) and its morphodynamics indicate the state of sediment flux (continuity) within a particular river reach. This underpins the basis of the methodology applied here.

5.2. Historic pattern of 2D river channel planform adjustment

The temporal pattern of river planform adjustments in many upland catchments has been linked to the incidence and severity of major floods (Wolman and Miller, 1960; Anderson and Calver, 1980; Milne, 1982; McEwen, 1989; Rumsby and Macklin, 1994; McEwen, 1994; Werritty and Hoey, 2004). High magnitude flood events can cause the erosion of river banks, initiate high sediment transport rates, leading to subsequent sediment deposition in the channel and on floodplains as peak flows recede (e.g., Fuller, 2008; Milan, 2012; Joyce et al., 2018; Heritage and Entwistle, 2019). Sediment deposition can block the channel promoting channel avulsion or chute and neck cut offs across the floodplain (Anderson and Calver, 1980; McEwen, 1994; Jones and Schumm, 1999). In the Wasdale catchment, boundary adjustments (avulsions, cut offs) occurred between 1860s–1950s and 1950s–1980, coinciding with four flood-rich periods in the Lake District region (Fig. 10). No boundary adjustments were identified from 1980 to 2010, despite this being a flood-rich period documented across the Lake District upland region (Fig. 10).

The relationship between the type and extent of planform adjustments is complicated by the fact that channel response to floods can vary from catchment to catchment (Warburton et al., 2002). First, the lack of flow gauge records in the Wasdale catchment limits the identification of catchment specific flood events that drive planform adjustments. Therefore, the lack of boundary adjustments observed after the 1980 period could be because there has not been a local flood of sufficient magnitude for geomorphic adjustment. The Raise Beck flood study (Johnson and Warburton, 2002) highlights that there is variability in river response to localised flood events compared to the Lake District

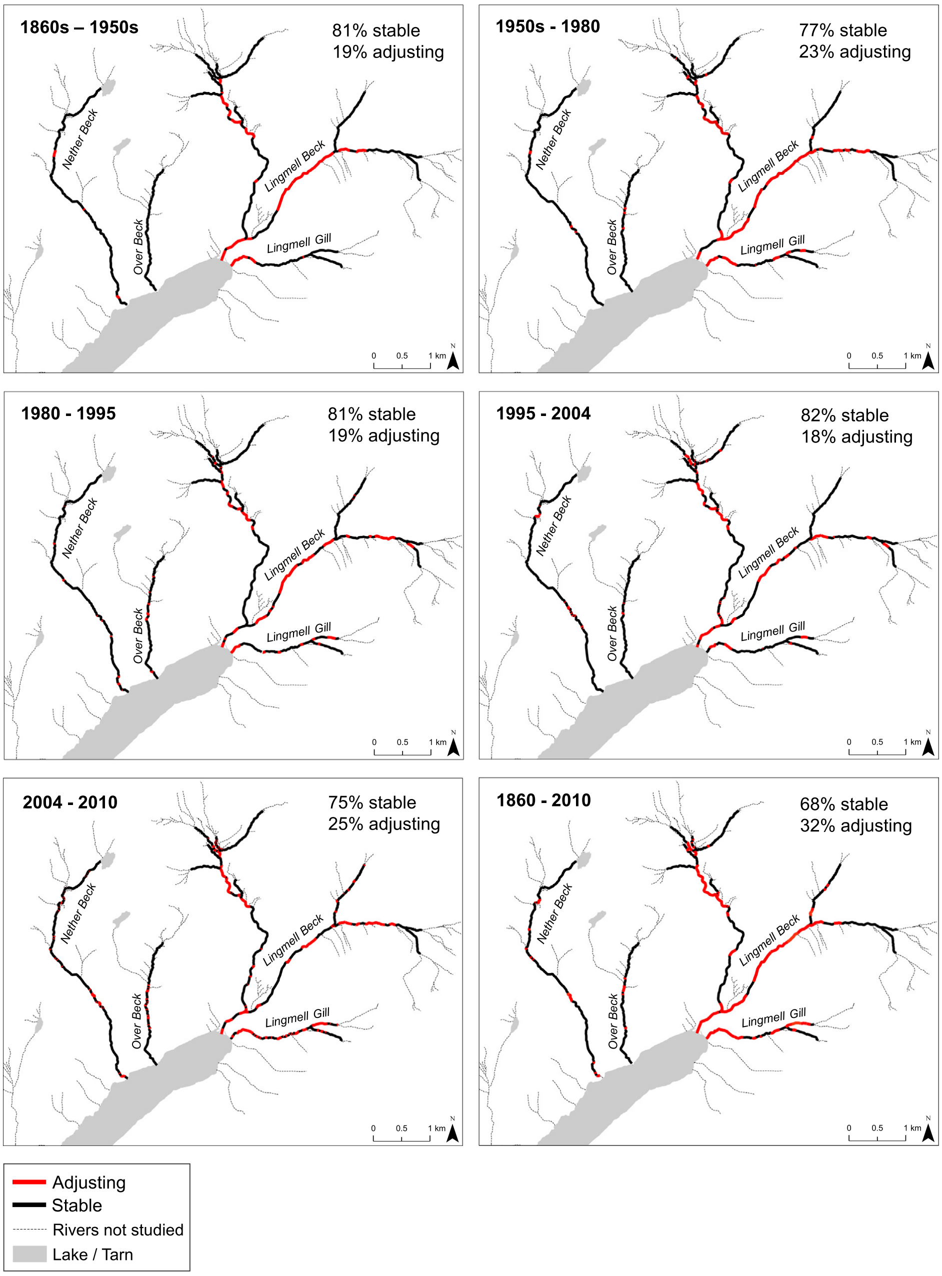


Fig. 11. Spatial pattern and percentage length of stable and adjusting reaches for all time periods of analysis in the Wasdale catchment, UK.

regional flood record (Fig. 10A). Recent work reconstructing detailed flood chronologies from lake sediment records (Chiverrell et al., 2019) and floodplain sediment cores (Jones et al., 2012; Fuller et al., 2019) provides an alternative means of developing catchment flood histories that are catchment specific and extend beyond the era of documented flood events. Second, the lack of observed boundary adjustments after the 1980 period could be because the channels have stabilised and therefore we only see bend, bar and width adjustments (Skinner and

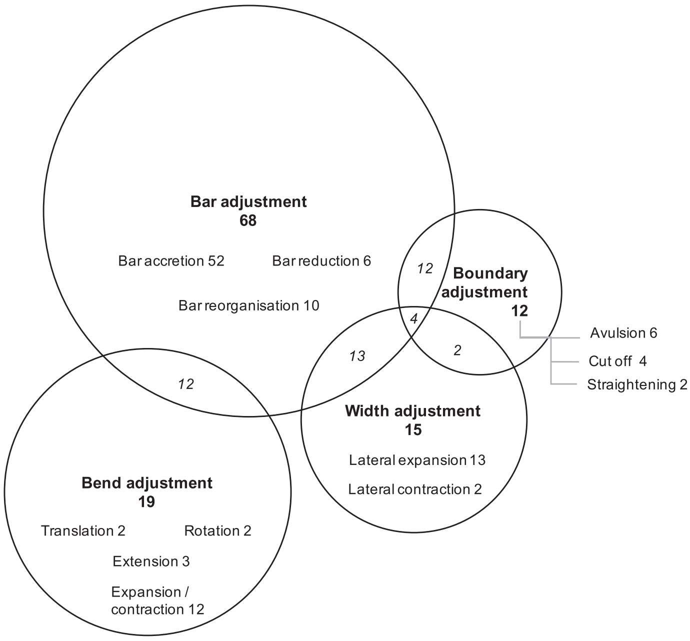


Fig. 12. Venn diagram showing the frequency of interactions between planform adjustment categories in the Wasdale catchment for the full period of analysis 1860s– 2010. Circles are proportional to the number of observed primary adjustments. Numbers in bold show the total frequency of adjustments for each group, numbers in italics represent the total number of combined adjustments between the groups.

Haycock, 2004). Similar results were found in Hoaroak Water, Exmoor, UK, where the channel showed relative stability and no major channel planform alteration 25 yr after a flood-initiated avulsion (Anderson and Calver, 1980; Werritty and Ferguson, 1980).

The temporal pattern of river planform adjustments is commonly linked to anthropogenic activity (Gilvear and Winterbottom, 1992; Surian and Rinaldi, 2003; Fryirs et al., 2009). Evidence of river straightening, embankments and bank reinforcements are present in the Wasdale catchment (Skinner and Haycock, 2004). Skinner and Haycock (2004), report straightening on Lingmell Beck occurred between the 1860s – 1899, therefore planform adjustments (e.g., boundary and bar adjustments) mapped over the 1860s–1950s could reflect channel recovery to artificial confinement. However, it is difficult to determine the direct impact of anthropogenic activity, as there is not a precise date of when straightening occurred, and there are different time intervals between historic sources used to map planform adjustments. Anthropogenic activity and contemporary river management could explain the lack of boundary adjustments observed after the 1980s period in the Wasdale catchment. For example, on Lingmell Beck the contemporary (~25 yr ago) construction of embankments restricts 2D lateral adjustment and might explain reaches of relative 2D stability observed after 1995 period (Fig. 11) (Skinner and Haycock, 2004). It is also important to recognise that channel modifications often pre-date the earliest available historic maps and channels may still be responding to 'legacy effects' long after cessation of the anthropogenic activity (Wohl, 2015). Consequently, in this context, it is difficult to state whether the threshold for boundary adjustment occurrence is the result of extrinsic controls (flood events, anthropogenic activity) or as a result of endogenic controls (e.g., progressive planform adjustment and gradient changes) that prime the reach before destabilisation (Brewer and Lewin, 1998).

The use of historical sources for river channel change detection are limited by the temporal availability of data and therefore should not be interpreted as a 'reference' or 'base' of channel planform (Ferguson, 1977). Historic maps and air photographs are often a composite of multiple datasets collected over months or years and therefore it is difficult to determine a single date of production, so 2D channel activity is mapped over 'periods', e.g., 1950s - 1980. Furthermore, the analysis of 2D historical channel planform often assumes that there is a linear or continuous change in channel planform between any two historical data comparisons (Lawler, 1993). However, channel planform adjustments can have different responses over different time scales and can be short-lived (intransitive), instantaneous, lagged, cumulative and progressive (Schumm and Lichty, 1965; Chappell, 1983). Therefore, planform adjustments might go unrecorded between two survey dates, or adjustments might be misinterpreted when comparing unequal time periods between available data (Ferguson, 1977). Instead, historical sources provide a useful record to understand how contemporary channel planform has evolved relative to the different dated historical data. This is demonstrated in the Wasdale catchment, where zones of persistent adjustment (e.g., Lingmell Beck) and relative stability (Gable Beck, Over Beck) are identified over the periods of observable data coverage (Fig. 11); this is useful to identify areas susceptible to future adjustment.

6. Conclusions

This paper presents a systematic catchment scale approach for quantifying the spatio-temporal patterns of 2D river planform stability and adjustment in response to exogenic forcing in an upland headwater catchment. The main results of the approach applied in the Wasdale case study show:

1. Marked contrasts were found between the geomorphic characteristics of 2D stable and adjusting reaches. In the Wasdale catchment, stable reaches ($n = 464$) had a mean channel width of 8 ± 5 m,

slope of 0.1 ± 0.08, local catchment area of 3.4 ± 3.3 km^2, valley bottom width of 110 ± 157 m and bankfull unit stream power of 424 ± 260 W m^{-2}. Adjustment reaches ($n = 584$) had a mean channel width of 11 ± 5.6 m, slope of 0.08 ± 0.07, local catchment area of 4.7 ± 4.1 km^2, valley bottom width of 170 ± 194 m and bankfull unit specific stream power of 325 ± 250 W m^{-2}.

2. The 2D laterally stable reaches were concentrated in confined low stream order channels, whereas unconfined high stream order channels (fourth and fifth order channels) in the floodplain valley transfer zone, were identified as zones of sediment storage (discontinuity) evidenced by a higher frequency of planform adjustments over the 150 yr study period.
3. Valley bottom width showed the greatest statistical difference for identifying planform adjustment types in third and fourth order channels and can be used to explain the location of boundary adjustments. This highlights the importance of confinement through the stream order hierarchy in influencing the accommodation space available for planform adjustment and stability.
4. Boundary adjustments were identified in 1860s – 1950s and 1950s – 1980 and coincided with the occurrence of flood-rich periods determined from long-term archival and gauged flood records in the Lake District upland region. After the 1980s no boundary adjustments were observed despite the occurrence of flood-rich periods suggesting the system has either (i) achieved local stability or a new equilibrium, (ii) has not been impacted by a flood of sufficient magnitude, or (iii) has been stabilised by anthropogenic modification restricting lateral adjustment. Further analysis should explore the impact of anthropogenic modification and response of the system to future extreme flood events.

The general methodology developed here can easily be applied to other catchments with commonly available historic maps, air photographs and DTM data. Future research should explore if the spatial patterns and controls of 2D planform adjustments are consistent across multiple catchments in a region, or if they are catchment specific. This will help identify relatively 'active' and 'stable' catchments that will inform a better understanding of sediment continuity, process-form behaviour, and aid with (i) the predictions of where adjustments might occur in the future, and (ii) the identification of locations for management or restoration priorities at a regional level.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the Lake District National Park Authority for allowing access and use of the air photographs in their offices. The 1995 air photograph is used with thanks from Natural England. The 2003-04 and 2009-10 air photographs are used under licence from © Bluesky International Ltd. The Environment Agency is thanked for providing flow data. Hannah M. Joyce was funded by a Natural Environmental Research Council UK Studentship Grant Number NE/L002590/1.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2020.107046.

References

Digimap, 2017. EDINA Digimap Data Collection. https://digimap.edina.ac.uk/ [accessed 2018].
Alber, A., Piégay, H., 2011. Spatial disaggregation and aggregation procedures for characterizing fluvial features at the network-scale: Application to the Rhône basin (France). Geomorphology 125 (3), 343–360.
Allen, J.R.L., 1965. A review of the origin and characteristics of recent alluvial sediments. Sedimentology 5 (2), 89–191.
Anderson, M.G., Calver, A., 1980. Channel plan changes following large floods. In: Cullingford, R.A., Davidson, D.A., Lewin, J. (Eds.), Timescales in Geomorphology. Wiley, Chichester, pp. 43–52.
Atherden, M., 1992. Upland Britain: A Natural History. Manchester University Press, p. 229.
Bagnold, R.A., 1966. An Approach to the Sediment Transport Problem from General Physics. Geological Survey Proffessional Paper 422-I. United States Government Printing Office, Washington, pp. 1–24.
Baker, V., Costa, J., 1987. Flood power. In: Mayer, L., Nash, D. (Eds.), Catastrophic Flooding. Allen and Unwin, Boston pp, pp. 1–20.
BGS, 2016. Britsh Geological Survey Superficial Geology. www.bgs.ac.uk/products/digitalmaps/digmapgb_drift.html [accessed 2019].
Bizzi, S., Lerner, D.N., 2012. Characterizing physical habitats in rivers using map-derived drivers of fluvial geomorphic processes. Geomorphology 169, 64–73.
Bizzi, S., Piégay, H., Demarchi, L., Van de Bund, W., Weissteiner, C., Gob, F., 2019. LiDAR-based fluvial remote sensing to assess 50–100-year human-driven channel changes at a regional level: the case of the Piedmont Region, Italy. Earth Surf. Process. Landf. 44 (2), 471–489.
Blacknell, C., 1981. River erosion in an upland catchment. Area 39–44.
Brewer, P.A., Lewin, J., 1998. Planform cyclicity in an unstable reach: complex fluvial response to environmental change. Earth Surface Processes and Landforms: the Journal of the British Geomorphological. Group 23 (11), 989–1008.
Brierley, G., Fryirs, K., 2005a. River Change, Geomorphology and River Management. Applications of the River Styles Framework. Blackwell Publishing, Oxford, pp. 186–202.
Brierley, G.J., Fryirs, K.A., 2005b. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publishing, Oxford, p. 416.
Brunsden, D., Thornes, J., 1979. Landscape sensitivity and change. T I Brit Geogr, pp. 463–484.
Carling, P., 1988. The concept of dominant discharge applied to two gravel-bed streams in relation to channel stability thresholds. Earth Surf. Process. Landf. 13 (4), 355–367.
Chappell, J., 1983. Thresholds and lags in geomorphologic changes. Aust. Geogr. 15, 357–366.
Chiverrell, R.C., Sear, D.A., Warburton, J., Macdonald, N., Schillereff, D.N., Dearing, J.A., Croudace, I.W., Brown, J., Bradley, J., 2019. Using lake sediment archives to improve understanding of flood magnitude and frequency: recent extreme flooding in North-west UK. Earth Surf. Process. Landf. 44 (12), 2366–2376.
Church, M., 1996. Channel Morphology and Typology. River Flows and Channel Forms: Selected Extracts from the Rivers Handbook. Blackwell Science, Boston, pp. 186–202.
Church, M., Jones, D., 1982. Channel bars in gravel-bed rivers. Gravel-bed rivers. John Wiley and Sons, Chichester, pp. 291–338.
Church, M., Rice, S.P., 2009. Form and growth of bars in a wandering gravel-bed river. Earth Surf. Process. Landf. 34 (10), 1422–1432.
Donovan, M., Miller, A., Baker, M., Gellis, A., 2015. Sediment contributions from floodplains and legacy sediments to Piedmont streams of Baltimore County, Maryland. Geomorphology 235, 88–105.
Donovan, M., Belmont, P., Notebaert, B., Coombs, T., Larson, P., Souffront, M., 2019. Accounting for uncertainty in remotely-sensed measurements of river planform change. Earth Sci. Rev. 193, 220–236.
Downs, P.W., Gregory, K.J., 1993. The sensitivity of river channels in the landscape system. In: Thomas, D.S.G., Allison, R.J. (Eds.), Landscape Sensitivity. Wiley, Chichester, pp. 15–30.
Downward, S., Gurnell, A., Brookes, A., 1994. A methodology for quantifying river channel planform change using GIS. IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological. Sciences 224, 449–456.
Dury, G., 1961. Bankfull discharge: an example of its statistical relationships. Hydrol. Sci. J. 6 (3), 48–55.
England, J., Gurnell, A.M., 2016. Incorporating catchment to reach scale processes into hydromorphological assessment in the UK. Water and Environment Journal 30 (1–2), 22–30.
European Commission, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities L327 1–72.
European Commission, 2007. European Commission Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood risks. Official Journal of the European Communities L 288 (/27).
Ferguson, R.I., 1977. Meander migration: equilibrium and change. River channel changes, pp. 235–248.
Ferguson, R.I., 1981. Channel forms and channel changes. In: Lewin, J. (Ed.), British Rivers. George Allen and Unwin, London, pp. 90–125.
Ferguson, R.I., 1987. Hydraulic and Sedimentary Controls of Channel Pattern. River Channels: Environments and Processes. Blackwell, Oxford, pp. 129–158.
Fryirs, K., Brierley, G.J., 2010. Antecedent controls on river character and behaviour in partly confined valley settings: Upper Hunter catchment, NSW, Australia. Geomorphology 117 (1–2), 106–120.
Fryirs, K.A., Brierley, G.J., 2012. Geomorphic Analysis of River Systems: An Approach to Reading the Landscape. John Wiley & Sons.
Fryirs, K., Spink, A., Brierley, G., 2009. Post-European settlement response gradients of river sensitivity and recovery across the upper Hunter catchment, Australia. Earth Surface Processes and Landforms 34 (7), 897–918.
Fryirs, K.A., Wheaton, J.M., Brierley, G.J., 2016. An approach for measuring confinement and assessing the influence of valley setting on river forms and processes. Earth Surf. Process. Landf. 41 (5), 701–710.

Fuller, I.C., 2008. Geomorphic impacts of a 100-year flood: Kiwitea Stream, Manawatu catchment, New Zealand. Geomorphology 98 (1–2), 84–95.
Fuller, I.C., Macklin, M.G., Toonen, W.H., Turner, J., Norton, K., 2019. A 2000 year record of palaeofloods in a volcanically-reset catchment: Whanganui River, New Zealand. Global and Planetary Change,181 102981, 1–12.
Gilvear, D.J., Winterbottom, S.J., 1992. Channel change and flood events since 1783 on the regulated River Tay, Scotland: implications for flood hazard management. Regulated Rivers: Research & Management 7 (3), 247–260.
Gurnell, A.M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, A.D., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., García de Jalón, D., González del Tánago, M., Grabowski, R.C., Gunn, I.D.M., Habersack, H., Hendriks, D., Henshaw, A. J., Klösch, M., Lastoria, B., Latapie, A., Marcinkowski, P., Martínez-Fernández, V., Mosselman, E., Mountford, J.O., Nardi, L., Okruszko, T., O'Hare, M.T., Palma, M., Percopo, C., Surian, N., van de Bund, W., Weissteiner, C., Ziliani, L., 2016. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquat. Sci. 78 (1), 1–16.
Harley, J.B., 1975. The Ordnance Survey Maps, a Descriptive Manual. Ordnance Survey, Southampton, p. 200.
Harvey, A.M., 1977. Event frequency in sediment production and channel change. River Channel Change, New York, John Wiley and Sons. 20, 301–310.
Harvey, A., 1997. Fluvial geomorphology of north-West England. In: Gregory, K.J. (Ed.), Fluvial Geomorphology of Great Britain. Geological Conservation Review Series, Chapman & Hall London, pp. 173–200.
Harvey, A.M., 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, Northwest England. Catena 42 (2–4), 225–250.
Heckmann, T., Haas, F., Abel, J., Rimböck, A., Becht, M., 2017. Feeding the hungry river: fluvial morphodynamics and the entrainment of artificially inserted sediment at the dammed river Isar, Eastern Alps, Germany. Geomorphology 291, 128–142.
Heritage, G., Entwistle, N., 2019. Drone based quantification of channel response to an extreme flood for a Piedmont Stream. Remote Sens. 11 (17), 1–16.
Hey, R.D., 1975. Design discharge for natural channels In: Hey R.D., Davies J.D. (Eds.), Science Technology and Environmental Management. Saxon House, Farnborough, pp. 71–81.
Hey, R.D., 1979. Dynamic process-response model of river channel development. Earth Surface Processes 4 (1), 59–72.
Hickin, E.J., 1978. Mean flow structure in meanders of the Squamish River, British Columbia. Can. J. Earth Sci. 15 (11), 1833–1849.
Higgitt, D.L., Warburton, J., Evans, M.G., 2001. Sediment transfer in upland environments. In: Higgitt, D.L., Lee, M.E. (Eds.), Geomorphological Processes and Landscape Change: Britain in the Last 1000 Years. Blackwell Publishers Ltd, Oxford, UK, pp. 190–214.
Hooke, J., 1977. The distribution and nature of changes in river channel patterns: The example of Devon. In: Gregory, K.J. (Ed.), River Channel Changes. John Wiley & Sons, Chichester, pp. 265–280.
Hooke, J.M., Redmond, C.E., 1989a. River-Channel changes in England and Wales. J Inst Water Env Man 3 (4), 328–335.
Hooke, J.M., Redmond, C.E., 1989b. Use of Cartographic Sources for Analysing River Channel Change with Examples from Britain, Historical Change of Large Alluvial Rivers: Western Europe. John Wiley & Sons, New York, pp. 79–93.
Hooke, J.M., Yorke, L., 2010. Rates, distributions and mechanisms of change in meander morphology over decadal timescales, River Dane, UK. Earth Surf. Process. Landf. 35 (13), 1601–1614.
Hughes, M.L., McDowell, P.F., Marcus, W.A., 2006. Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. Geomorphology 74 (1–4), 1–16.
Hughes, R.M., Kaufmann, P.R., Weber, M.H., 2011. National and regional comparisons between Strahler order and stream size. J. N. Am. Benthol. Soc. 30 (1), 103–121.
Ibisate, A., Ollero, A., Diaz, E., 2011. Influence of catchment processes on fluvial morphology and river habitats. Limnetica 30 (2), 169–182.
Jackson, R.G., 1975. Hierarchical attributes and a unifying model of bed forms composed of cohesionless material and produced by shearing flow. Geol. Soc. Am. Bull. 86 (11), 1523–1533.
Johnson, R.M., Warburton, J., 2002. Flooding and geomorphic impacts in a mountain torrent: Raise Beck, Central Lake District, England. Earth Surf. Process. Landf. 27 (9), 945–969.
Jones, L., Schumm, S., 1999. Causes of avulsion: an overview, Fluvial sedimentology VI. Spec. Publ. Int. Assoc. Sedimentol, pp. 171–178.
Jones, A.F., Macklin, M.G., Brewer, P.A., 2012. A geochemical record of flooding on the upper River Severn, UK, during the last 3750 years. Geomorphology 179, 89–105.
Joyce, H.M., Hardy, R.J., Warburton, J., Large, A.R., 2018. Sediment continuity through the upland sediment cascade: geomorphic response of an upland river to an extreme flood event. Geomorphology 317, 45–61.
Knighton, A.D., 1999. Downstream variation in stream power. Geomorphology 29 (3–4), 293–306.
Kondolf, G.M., 1997. PROFILE: hungry water: effects of dams and gravel mining on river channels. Environ. Manag. 21 (4), 533–551.
Lawler, D.M., 1993. The measurement of river bank erosion and lateral channel change: a review. Earth Surf. Process. Landf. 18 (9), 777–821.
Lea, D.M., Legleiter, C.J., 2016. Mapping spatial patterns of stream power and channel change along a gravel-bed river in northern Yellowstone. Geomorphology 252, 66–79.
Leopold, L.B., Maddock, T., 1953. The hydraulic geometry of stream channels and some physiographic implications (Vol. 252). US Governmnt Printing. Office. 57.
Leopold, L.B. and Miller, J.P., 1956. Ephemeral streams: Hydraulic factors and their relation to the drainage net (Vol. 282). US Government Printing Office.
Leopold, L.B., Wolman, M.G., 1957a. The braided river, River Channel Patterns: braided, meandering and straight. Geological Survey Professional Paper 282-B, Washington, pp. 39–53.
Leopold, L.B., Wolman, M.G., 1957b. River Channel Patterns: Braided, Meandering, and Straight. US Government Printing Office.
Lewin, J., 1977. Channel pattern changes. In: Gregory, K.J. (Ed.), River Channel Changes. John Wiley & Sons, Chichester, New York, Brisbane, Toronto, pp. 167–184.
Lewin, J., 1987. Historical river channel changes. Palaeohydrology in Practice: A River Basin Analysis. John Wiley and Sons New York. 1987. p 161-175, 8 fig, 1 tab. In: Gregory, K.J., Lewin, J., Thornes, J.B. (Eds.), ref. 17. John Wiley & Sons, Chichester, pp. 161–175.
Lewin, J., Hughes, D., 1976. Assessing channel change on Welsh rivers. Cambria 3 (1), 1–10.
Lewin, J., Hughes, D., Blacknell, C., 1977. Incidence of River Erosion. Area 9 (3), 177–180.
Lisenby, P.E., Fryirs, K.A., 2016. Catchment- and reach-scale controls on the distribution and expectation of geomorphic channel adjustment. Water Resour. Res. 52 (5), 3408–3427.
Macdonald, N., Sangster, H., 2017. High-magnitude flooding across Britain since AD 1750. Hydrol Earth Syst Sc 21 (3), 1631–1650.
Macklin, M.G., Lewin, J., 1989. Sediment transfer and transformation of an alluvial valley floor: the River South Tyne, Northumbria, UK. Earth Surface Processes and Landforms 14 (3), 233–246.
Macklin, M.G., Lewin, J., 1998. Channel, floodplain and drainage basin response to environmental change. In: Thorne, C.R., Hey, R.D., Newson, M.D. (Eds.), Applied Fluvial Geomorphology for River Engineering and Management. John Wiley & Sons, Chichester, UK, pp. 54–69.
Macklin, M.G., Rumsby, B.T., Heap, T., 1992. Flood alluviation and entrenchment: Holocene valley-floor development and transformation in the British uplands. Geol. Soc. Am. Bull. 104 (6), 631–643.
Macklin, M., Passmore, D., Newson, M., 1998. Controls of Short and Long Term River Instability: Processes and Patterns in Gravel-Bed Rivers, the Tyne Basin, Northern England. Water Resources Publications, LLC Colorado, pp. 257–278.
Marchi, L., Cavalli, M., Amponsah, W., Borga, M., Crema, S., 2016. Upper limits of flash flood stream power in Europe. Geomorphology 272, 68–77.
Marcus, W.A., Fonstad, M.A., 2010. Remote sensing of rivers: the emergence of a subdiscipline in the river sciences. Earth Surf. Process. Landf. 35 (15), 1867–1872.
Martínez-Fernández, V., del Tánago, M.G., de Jalón, D.G., 2019. Selecting geomorphic variables for automatic river segmentation: Trade-offs between information gained and effort required. Geomorphology 329, 248–258.
McEwen, L.J., 1989. River Channel Changes in Response to Flooding in the Upper River Dee Catchment, Aberdeenshire, over the Last 200 Years. Floods: Hydrological. Sedimentological and Geomorphological Implications. John Wiley & Sons, New York, pp. 219–238.
McEwen, L.J., 1994. Channel Planform Adjustment and Stream Power Variations on the Middle River Coe, Western Grampian Highlands, Scotland. Catena 21 (4), 357–374.
Milan, D.J., 2012. Geomorphic impact and system recovery following an extreme flood in an upland stream: Thinhope Burn, northern England, UK. Geomorphology 138 (1), 319–328.
Miller, S.N., Guertin, D.P., Goodrich, D.C., 2002. Deriving stream channel morphology using GIS-based watershed analysis. GIS for Water Resource and Watershed Management. CRC Press, London, pp. 71–78.
Milne, J., 1982. River Channel Change in the Harthope Valley, Northumberland, since 1897, University of Newcastle upon Tyne. Newcastle, UK.
Milne, J., 1983. Patterns of confinement in some stream channels of upland Britain. Geografiska Annaler. Series A. Physical Geography 65 (1/2), 67–83.
Milton, E., Gilvear, D., Hooper, I., 1995. Investigating change in fluvial systems using remotely sensed data. In: Gurnell, A.M., Petts, G.E. (Eds.), Changing River Channels. John Wiley & Sons, Chichester, pp. 276–301.
Montgomery, D.R., Buffington, J.M., 1993. Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition, Department of Geological Sciences and Quaternary Research Centre. University of Washington, Washington.
Nanson, G.C., Knighton, A.D., 1996. Anabranching rivers: their cause. character and classification. Earth surface processes and landforms 21 (3), 217–239.
Newson, M., 1980. The geomorphological effectiveness of floods—a contribution stimulated by two recent events in mid-Wales. Earth Surface Processes 5 (1), 1–16.
Newson, M.D., 1989. Flood effectiveness in river basins: progress in Britain in a decade of drought. In: Beven, K., Carling, P. (Eds.), Floods: Hydrological, Sedimentological and Geomorphological Implications. Wiley, Chichester, pp. 151–169.
Newson, M., 1997. Time, scale and change in river landscapes: the jerky conveyor belt. Landsc. Res. 22 (1), 13–23.
O'Brien, G.R., Wheaton, J.M., Fryirs, K., Macfarlane, W.W., Brierley, G., Whitehead, K., Gilbert, J., Volk, C., 2019. Mapping Valley bottom confinement at the network scale. Earth Surf. Process. Landf. 44 (9), 1828–1845.
Passmore, D.G., Macklin, M.G., Brewer, P.A., Lewin, J., Rumsby, B.T., Newson, M.D., 1993. Variability of late Holocene braiding in Britain. Geol. Soc. Lond., Spec. Publ. 75 (1), 205–229.
Pattison, I., Lane, S.N., 2012. The relationship between Lamb weather types and long-term changes in flood frequency, River Eden, UK. Int. J. Climatol. 32 (13), 1971–1989.
Petts, G.E., 1979. Complex response of river channel morphology subsequent to reservoir construction. Prog. Phys. Geogr. 3, 329–362.
Petts, G.E., Möller, H., Roux, A.L., 1989. Historical Change of Large Alluvial Rivers: Western Europe. John Wiley & Sons, Chichester.
Piégay, H., Chabot, A., Le Lay, Y.F., 2018. Some comments about resilience: From cyclicity to trajectory, a shift in living and nonliving system theory. Geomorphology https://doi.org/10.1016/j.geomorph.2018.09.018.
Reinfelds, I., Cohen, T., Batten, P., Brierley, G., 2004. Assessment of downstream trends in channel gradient, total and specific stream power: a GIS approach. Geomorphology 60 (3–4), 403–416.
Rice, S.P., Church, M., Wooldridge, C.L., Hickin, E.J., 2009. Morphology and evolution of bars in a wandering gravel-bed river; lower Fraser river, British Columbia, Canada. Sedimentology 56 (3), 709–736.

Richards, K., 1982. Rivers: Form and Process in Alluvial Channels. Methuen, London.
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: the Morphological Quality Index (MQI). Geomorphology 180, 96–108.
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2015a. A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology 251, 122–136.
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., Nardi, L., Lastoria, B., 2015b. IDRAIM: A Methodological Framework for Hydromorphological Analysis and Integrated River Management of Italian Streams. Engineering Geology for Society and Territory, Vol 3: River Basins, Reservoir Sedimentation and Water Resources, pp. 301–304.
Rinaldi, M., Gurnell, A., Del Tánago, M.G., Bussettini, M., Hendriks, D., 2016. Classification of river morphology and hydrology to support management and restoration. Aquat. Sci. 78 (1), 17–33.
Robson, A., Reed, D., 1999. Flood Estimation Handbook. Statistical Procedures for Flood Frequency Estimation. Institute of Hydrology, Oxfordshire, p. 3.
Rosgen, D.L., 1994. A classification of natural rivers. Catena 22 (3), 169–199.
Rumsby, B., Macklin, M.G., 1994. Channel and floodplain response to recent abrupt climate change: the Tyne basin, northern England. Earth Surf. Process. Landf. 19 (6), 499–515.
Schumm, S.A., 1969. River metamorphosis. J. Hydraul. Div. 95 (1), 255–274.
Schumm, S.A., 1977. The Fluvial System. John Wiley and Sons, New York.
Schumm, S.A., 1985. Patterns of alluvial rivers. Annu. Rev. Earth Planet. Sci. 13 (1), 5–27.
Schumm, S.A., Lichty, R.W., 1965. Time, space, and causality in geomorphology. Am. J. Sci. 263 (2), 110–119.
Sear, D.A., Newson, M.D., 2003. Environmental change in river channels: a neglected element. Towards geomorphological typologies, standards and monitoring. Sci. Total Environ. 310 (1–3), 17–23.
Sear, D.A., Newson, M.D., Thorne, C.R., 2003. Guidebook of applied fluvial geomorphology. 0727741012. DEFRA, London.
Skinner, K.S., Haycock, N.E., 2004. Wasdale – fluvial audit of the Lingmell Beck and Mosedale Beck systems. Prepared for the National Trust. Haycock Associates Limited, Pershore.
Slingerland, R., Smith, N.D., 2004. River avulsions and their deposits. Annu. Rev. Earth Planet. Sci. 32, 257–285.
Snyder, N.P., Kammer, L.L., 2008. Dynamic adjustments in channel width in response to a forced diversion: Gower Gulch, Death Valley National Park, California. Geology 36 (2), 187–190.
Stouthamer, E., Berendsen, H.J., 2001. Avulsion frequency, avulsion duration, and interavulsion period of Holocene channel belts in the Rhine-Meuse delta, the Netherlands. J. Sediment. Res. 71 (4), 589–598.
Strahler, A.N., 1952. Hypsometric (Area Altitude) analysis of erosional topology. Geol. Soc. Am. Bull. 63, 1117–1142.
Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union 38 (6), 913–920.
Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50 (4), 307–326.
Surian, N., Righini, M., Lucía, A., Nardi, L., Amponsah, W., Benvenuti, M., Borga, M., Cavalli, M., Comiti, F., Marchi, L., Rinaldi, M., 2016. Channel response to extreme floods: insights on controlling factors from six mountain rivers in northern Apennines, Italy. Geomorphology 272, 78–91.
Thomas, M.F., 2001. Landscape sensitivity in time and space—an introduction. Catena 42 (2–4), 83–98.
Thoms, M.C., Piégay, H., Parsons, M., 2018. What do you mean,'resilient geomorphic systems'? Geomorphology 305, 8–19.
Thompson, C., Croke, J., 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer valley, southeast Queensland, Australia. Geomorphology 197, 156–169.
Thorne, C.R., 1997. Channel types and morphological classification. In: Thorne, C.R., Hey, R.D., Newson, M.D. (Eds.), Applied Fluvial Geomorphology for River Engineering and Management. John Wiley & Sons, Chichester, UK, pp. 175–222.
Warburton, J., Danks, M., Wishart, D., 2002. Stability of an upland gravel-bed stream, Swinhope Burn, Northern England. Catena 49 (4), 309–329.
Watkins, S., Whyte, I., 2008. Extreme flood events in upland catchments in Cumbria since 1600: the evidence of historical records. North West Geogr 8 (1), 33–41.
Werritty, A., Ferguson, R., 1980. Pattern changes in a Scottich braided river over 1, 30 and 200 years. In: Cullingford, R., Davidson, D., Lewin, J. (Eds.), Timescale in Geomorphology. John Wiley & Sons, Great Britain, pp. 53–68.
Werritty, A., Hoey, T., 2004. Trends and Issues: Geomorphological Changes and Trends in Scotland - Trends in River Channels and Processes. Scottish Natural Heritage, Edingburgh.
Werritty, A., Leys, K.F., 2001. The sensitivity of Scottish rivers and upland valley floors to recent environmental change. Catena 42 (2–4), 251–273.
Wilson, P., 2005. Paraglacial rock-slope failures in Wasdale, western Lake District, England: morphology, styles and significance. Proc. Geol. Assoc. 116 (3–4), 349–361.
Winterbottom, S.J., 2000. Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland. Geomorphology 34 (3), 195–208.
Wishart, D., 2004. A Combined Catchment and Reach-Based Assessment of Historical Channel Planform Change in a UK Upland Gravel-Bed River. Durham University, Durham theses.
Wishart, D., Warburton, J., Bracken, L., 2008. Gravel extraction and planform change in a wandering gravel-bed river: the River Wear, Northern England. Geomorphology 94 (1–2), 131–152.
Wohl, E., 2015. Legacy effects on sediments in river corridors. Earth Sci. Rev. 147, 30–53.
Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. The Journal of Geology 68 (1), 54–74.
Zar, J., 2010. H. Biostatistical Analysis. Pearson Prentice Hall, Comparing Simple Linear Regression Equations.

Supplementary Data

The supplementary information below provides additional context for the development and application of the methodology in the Wasdale case study and other UK case studies:

- Historic map and air photograph data coverage and availability for the UK (Table S1).
- Station-point interval spacing tests (Table S2) and the geomorphic characteristics extracted at each resolution (Fig. S1)
- Slope upstream / downstream distance testing values (Table S3) and figure showing change in slope values between different distance tests (Fig. S2)
- Geo-referencing error assessment of the air photographs and historic maps used in the Wasdale case study (Table S4).
- Discharge-area relationship for different flow events in the Lake District upland region (Fig. S3). Discharge data is used to calculate unit stream power in the Wasdale case study, in this case study the 2 yr return interval is used.

Table S1. Details of historical maps and air photographs available for the UK (modified from Hooke and Redmond, 1989b).

	Date	Map Source	Scale	Coverage of UK	Reference
	Late 16th Century, majority <1700	Estate	Usually 1:2376	Over 20,000 available for consultation in England	Harley (1972)
	18th and 19th Century	Enclosure		Variable in England and Wales	Tate (1978)
	1840s	Tithe	Usually 1:2376 or 1:4752	3/4 of England and Wales	Kain and Prince (1985)
	Post 1794	Deposited plans	Min. scale 1:15,840 after 1807	Britain	Harley (1972)
	18th and 19th Century	County	1:63,360; 1:31,689	England and Wales	Skelton (1970); Rodger (1972)
	1747 - 1755	Military Survey of Scotland (Roy)	1:36,000	Scotland	Moir (1973)
	1795 - 1755	Ordnance Survey Old series 1st ed.	1:63,360	England and Wales	Harley (1965)
	1840 - 1926	Ordnance Survey New Series 2nd – 4th ed.	1:63,360	England and Wales	Harley (1965)
♦	1854 - 1949	County Series 1st ed. – 3rd revision	1:2,500; 1:10,560	England and Wales	Harley (1965)
♦	1943 - 1992	National Grid Series Edition A - E	1:1,250, 1:2,500	England and Wales	Harley (1975)
	1948 - 1982	National Grid Imperial 1st Edition. (1st – 3rd Revision)	1:10 560	England and Wales	
♦	1969 - 1996	National Grid 1:10,000 series, fully metric, 1st edition	1:10,000	England and Wales	
	1958 - 1996	National Grid 1:10,000 metric and 1:10,560 imperial latest editions	1:10,560 and 1:10,000	UK	
♦	1960s - present	Air photographs	1:250 - 1:200,000	High – covers England and Wales – composite of images	

♦ sources of data used in the Wasdale case study

Table S2. Different resolution station point (SP) spacing intervals (m) tested in the Wasdale catchment case study.

Stream order	**High resolution**		**Medium resolution**		**Low resolution**	
	SP interval (m)	*n*	*SP interval (m)*	*n*	*SP interval (m)*	*n*
2	100	55	200	28	400	24
3	200	54	300	39	600	25
4	300	26	400	19	800	12
5	400	3	500	3	1000	2
SP total		138		89		63

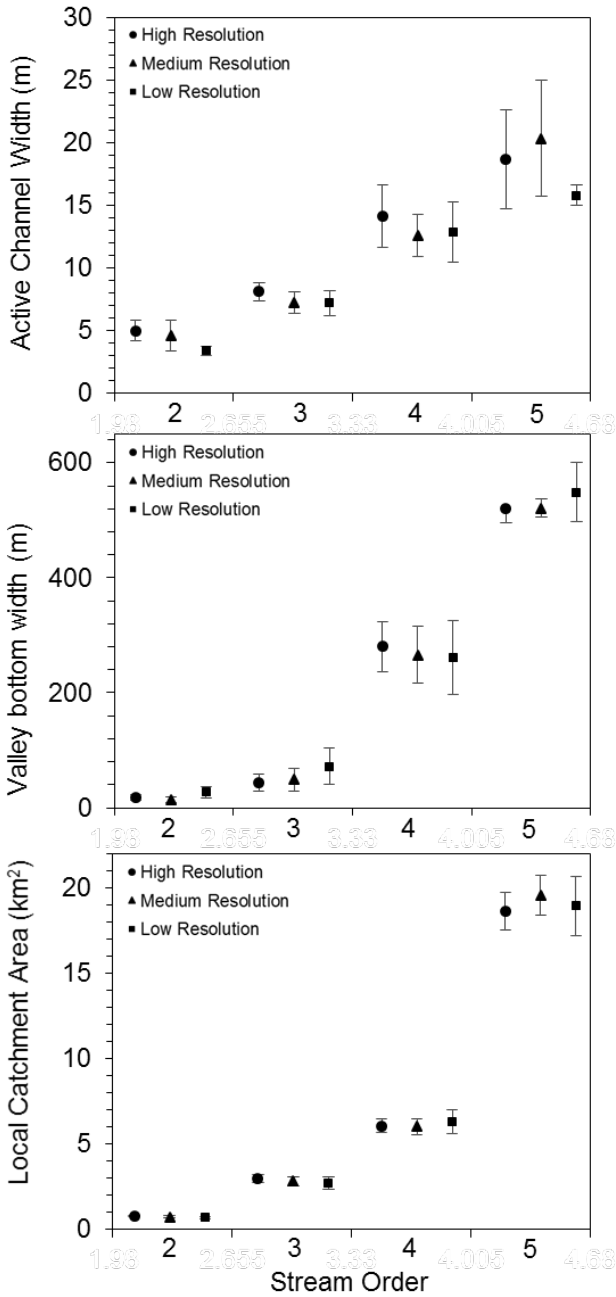


Figure S1. Examples of mean geomorphic characteristics extracted at high, medium and low-resolution station point spacing intervals (Table S2) in the Wasdale catchment. No statistically significant differences were identified between the three resolution station point intervals at the 0.05 and 0.01 confidence level.

Table S3. Slope sensitivity analysis: distance elevation values are extracted upstream and downstream of the station points (SPs positioned at low resolution spacing interval) in the Wasdale catchment. Three distances were tested to see how it affected the calculation of slope. No statistical differences were identified between the three distances slope values were produced so distance 3 is used to extract elevation values upstream and downstream of station points in the Wasdale catchment.

Stream order	Distance 1 (m)	Distance 2 (m)	Distance 3 (m)
2	25	50	100
3	50	100	200
4	75	150	300
5	100	200	400

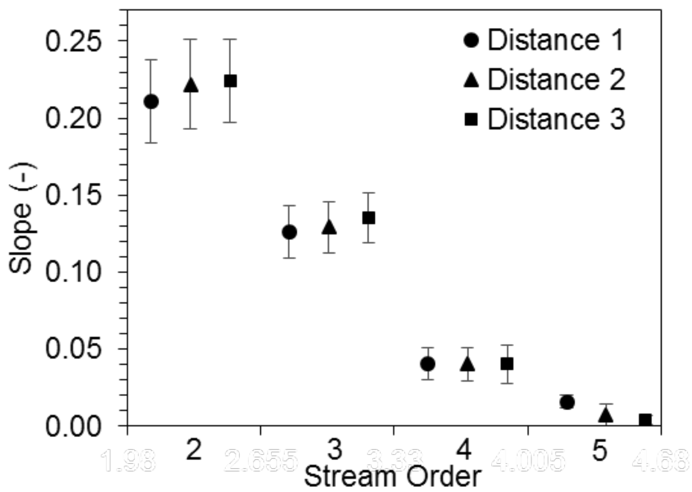


Figure S2. Mean slope values extracted over different distances (Table S2) for each stream order. There were no statistically significant differences between the three distances tested at the 0.05 and 0.01 confidence level.

Table S4. Root Mean Square Error (RMSE) and local test point error following second order polynomial transformation of maps and air photographs to an OS base map.

Year of map / photo	RMSE (m)	Test Point (Local) Error (m) Mean	Std. Dev.
1860s	2.6	3.7	2.0
1950s	3.3	4.0	1.6
1980	1.5	2.7	1.5
1995	1.4	2.0	1.0
2004	0.8	1.9	1.4
2010	0.8	1.4	1.4

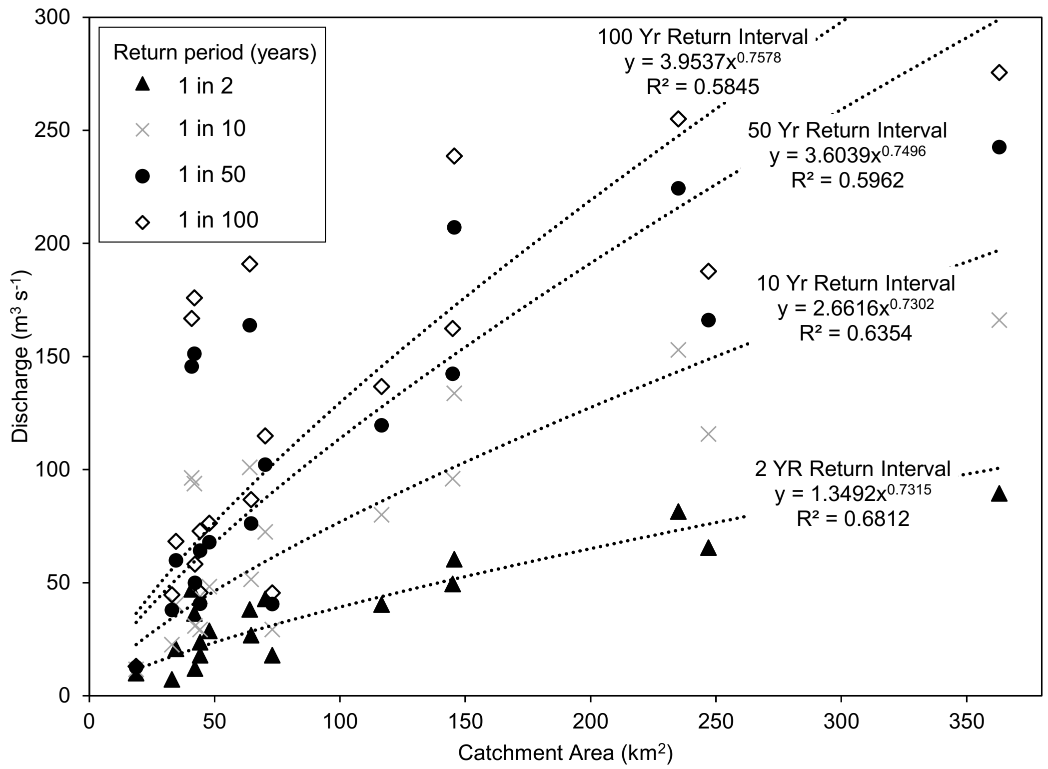


Figure S3. Discharge-area relationship for the 1 in 2, 1 in 10, 1 in 50 and 1 in 100 yr flow event in the Lake District upland region. Generated using 19 gauging stations located throughout the upland region. Discharge data sourced from the UK Environment Agency.

References

Harley, J.B., 1965. The re-mapping of England, 1700 - 1800. Imago Mundi 19, 56–67.

Harley, J.B., 1972. Maps for the Local Historian: A Guide to the British Sources. National Council of Social Service, London.

Harley, J.B., 1975. The Ordnance Survey Maps, a Descriptive Manual. Ordnance Survey, Southampton, p. 200

Kain, R.J., Prince, H.C., 1985. The Tithe Surveys of England and Wales. Cambridge University Press. Cambridge, p. 344.

Moir, D.G., Inglis, H.R., 1973. The early maps of Scotland to 1850 (Vol. 1). Royal Scottish Geographical Society, Scotland.

Rodger, E.M., 1972. The Large-Scale County Maps of the British Isles, 1956 - 1980: A Union List. Bodleian Library, Oxford.

Skelton, R.A., 1970. County Atlases of the British Isles, 1579-1850. Carta Press, London.

Tate, W.E., 1978. A Domesday of English Enclosure Acts and Awards. University of Reading, Reading.

Appendix C

Data tables: statistically significant differences between geomorphic characteristics and planform adjustment categories:

- Tables C.1 – C.4: Statistically significant differences between mean geomorphic characteristics (slope, specific stream power, channel width and catchment area) extracted from the station points for each stream order and catchment. Data is discussed in Chapter 6, Section 6.4.2.
- Tables C.5 – C.8: Statistically significant differences between planform adjustments, stable reaches, geomorphic variables (slope, valley bottom width, channel width and specific stream power) and channel stream order. Data is discussed in Chapter 6, Section 6.6.1.

Table C.1. Statistically significant differences between mean slope values extracted at the SPs for each stream order and catchment studied.

Dots indicate the presence of statistically significant differences.

	BASSENTHWAITE	CALDER	CALDEW	CAWDALE	CONISTON	CRUMMOCK	DUDDON	ENNERDALE	ESK	HAWESWATER	KENT	SLEDDALE	SPRINT	SWINDALE	ULLSWATER	WASDALE	WINDERMERE
BASSENTHWAITE																	
CALDER																	
CALDEW																	
CAWDALE																	
CONISTON																	
CRUMMOCK																	
DUDDON																	
ENNERDALE																	
ESK																	
HAWESWATER		● ♦	●														
KENT																	
SLEDDALE																	
SPRINT																	
SWINDALE																	
ULLSWATER			●														
WASDALE	● ♦ +	● ♦	●			● ♦	●	♦	●			●			♦		
WINDERMERE		●	●														

Presence of statistically significant difference		n*
2nd Order	●	12
3rd Order	♦	6
4th Order	+	1

Table C.2. Statistically significant differences between mean catchment area values extracted at the SPs for each stream order and catchment in the Lake District study region. Dots indicate the presence of statistically significant differences.

	BASSENTHWAITE	CALDER	CALDEW	CAWDALE	CONISTON	CRUMMOCK	DUDDON	ENNERDALE	ESK	HAWESWATER	KENT	SLEDDALE	SPRINT	SWINDALE	ULLSWATER	WASDALE	WINDERMERE
BASSENTHWAITE		♦															
CALDER	●																
CALDEW	●	♦															
CAWDALE		♦	●														
CONISTON	+	♦															
CRUMMOCK	●	♦															
DUDDON		♦															
ENNERDALE	♦		● ♦		♦	♦											
ESK	+	♦	●			●		♦									
HAWESWATER		● ♦	●			●		♦									
KENT	+	♦	●					♦									
SLEDDALE		● ♦	●			●											
SPRINT	+	♦						♦									
SWINDALE	+	♦	●				+	♦									
ULLSWATER	♦ + -	● ♦	●			●	+	♦									
WASDALE	♦ + -	● ♦	● +			●	● +	♦									
WINDERMERE	♦ + - □	♦	●			●		♦									

Presence of statistically significant difference		n*
2nd Order	●	24
3rd Order	♦	30
4th Order	+	12
5th Order	-	3
6th Order	□	1

Table C.3. Statistical differences between mean channel width (2010) for each stream order and each catchment. Dots indicate the presence of statistically significant differences.

	BASSENTHWAITE	CALDER	CALDEW	CAWDALE	CONISTON	CRUMMOCK	DUDDON	ENNERDALE	ESK	HAWESWATER	KENT	SLEDDALE	SPRINT	SWINDALE	ULLSWATER	WASDALE	WINDERMERE
BASSENTHWAITE					●			● ♦									
CALDER	♦				●			♦									
CALDEW					●			♦ +									
CAWDALE					●			♦									
CONISTON								♦ +									
CRUMMOCK					●			♦ +									
DUDDON					●			♦									
ENNERDALE					●												
ESK					●			♦									
HAWESWATER					●			♦									
KENT					●			♦ +									
SLEDDALE					●			♦									
SPRINT					●			♦ +									
SWINDALE					●			♦ +									
ULLSWATER	-	♦			● ♦			♦ +									
WASDALE					●			♦									
WINDERMERE	-				●			♦ +									

Presence of statistically significant difference		n*
2nd Order	●	17
3rd Order	♦	19
4th Order	+	8
5th Order	-	2
6th Order	□	0

Table C.4. Statistical differences between specific stream power, stream order and the 17 catchments studied. Dots indicate the presence of statistically significant differences.

	BASSENTHWAITE	CALDER	CALDEW	CAWDALE	CONISTON	CRUMMOCK	DUDDON	ENNERDALE	ESK	HAWESWATER	KENT	SLEDDALE	SPRINT	SWINDALE	ULLSWATER	WASDALE	WINDERMERE
BASSENTHWAITE				●													
CALDER				●													
CALDEW																	
CAWDALE																	
CONISTON				●													
CRUMMOCK				●													
DUDDON				●													
ENNERDALE				●													
ESK				●													
HAWESWATER		♦						♦									
KENT																	
SLEDDALE				●													
SPRINT				●													
SWINDALE				●													
ULLSWATER				●													
WASDALE				●													
WINDERMERE				●				♦									

Presence of statistically significant difference		n*
2nd Order	●	13
3rd Order	♦	3
4th Order	+	0
5th Order	-	0
6th Order	□	0

Table C.5. Statistically significant differences (p value <0.005) between planform adjustments, stable reaches, geomorphic variables, channel stream order and catchment for channel slope. Dots indicate the presence of statistically significant differences.

SLOPE		BASSENTHWAITE	CALDER	CALDEW	CALDER	CAWDALE	CONISTON	CRUMMOCK	DUDDON	ENNERDALE	ESK	HAWESWATER	KENT	SLEDDALE	SPRINT	SWINDALE	ULLSWATER	WASDALE	WINDERMERE
STREAM ORDER 2	Bar Adjustment vs Bend Adjustment										●							●	
	Bar Adjustment vs Boundary Adjustment							●											
	Bar Adjustment vs Width Adjustment																	●	
	Bar Adjustment vs Stable	●										●	●						●
	Bend Adjustment vs Width Adjustment																		
	Bend Adjustment vs Boundary Adjustment																		
	Bend Adjustment vs Stable	●																	
	Boundary Adjustment vs Width Adjustment															●			
	Boundary Adjustment vs Stable							●											
	Width Adjustment vs Stable																		
STREAM ORDER 3	Bar Adjustment vs Bend Adjustment	●									●	●			●				
	Bar Adjustment vs Boundary Adjustment																		
	Bar Adjustment vs Width Adjustment	●								●				●					
	Bar Adjustment vs Stable									●	●	●							●
	Bend Adjustment vs Width Adjustment																		
	Bend Adjustment vs Boundary Adjustment	●												●					
	Bend Adjustment vs Stable	●									●	●							
	Boundary Adjustment vs Width Adjustment	●																	
	Boundary Adjustment vs Stable																		
	Width Adjustment vs Stable	●								●	●	●		●					
STREAM ORDER 4	Bar Adjustment vs Bend Adjustment														●		●		
	Bar Adjustment vs Boundary Adjustment																	●	
	Bar Adjustment vs Width Adjustment																		
	Bar Adjustment vs Stable																		
	Bend Adjustment vs Width Adjustment																		
	Bend Adjustment vs Boundary Adjustment																		
	Bend Adjustment vs Stable	●													●		●		
	Boundary Adjustment vs Width Adjustment																		
	Boundary Adjustment vs Stable																		
	Width Adjustment vs Stable														●				
	SUM	*9*						*2*		*3*	*5*	*5*	*1*	*3*	*4*	*1*	*2*	*3*	*2*

Table C.6. Statistically significant differences (p value <0.005) between planform adjustments, stable reaches, geomorphic variables, channel stream order and catchment for channel width. Dots indicate the presence of statistically significant differences.

Channel width		BASSENTHWAITE	CALDER	CALDEW	CALDER	CAWDALE	CONISTON	CRUMMOCK	DUDDON	ENNERDALE	ESK	HAWESWATER	KENT	SLEDDALE	SPRINT	SWINDALE	ULLSWATER	WASDALE	WINDERMERE
STREAM ORDER 2	Bar Adjustment vs Bend Adjustment	•						•			•						•		•
	Bar Adjustment vs Boundary Adjustment									•									
	Bar Adjustment vs Width Adjustment									•									
	Bar Adjustment vs Stable										•		•	•				•	
	Bend Adjustment vs Width Adjustment	•								•									
	Bend Adjustment vs Boundary Adjustment									•									•
	Bend Adjustment vs Stable	•												•				•	•
	Boundary Adjustment vs Width Adjustment									•									
	Boundary Adjustment vs Stable									•									
	Width Adjustment vs Stable									•								•	
STREAM ORDER 3	Bar Adjustment vs Bend Adjustment	•						•											
	Bar Adjustment vs Boundary Adjustment																	•	
	Bar Adjustment vs Width Adjustment									•				•					•
	Bar Adjustment vs Stable						•	•		•								•	•
	Bend Adjustment vs Width Adjustment	•																•	
	Bend Adjustment vs Boundary Adjustment									•				•					•
	Bend Adjustment vs Stable	•																	
	Boundary Adjustment vs Width Adjustment																	•	•
	Boundary Adjustment vs Stable									•									•
	Width Adjustment vs Stable									•				•				•	•
STREAM ORDER 4	Bar Adjustment vs Bend Adjustment	•																	
	Bar Adjustment vs Boundary Adjustment	•																•	
	Bar Adjustment vs Width Adjustment										•				•				
	Bar Adjustment vs Stable																		
	Bend Adjustment vs Width Adjustment																		
	Bend Adjustment vs Boundary Adjustment	•																	
	Bend Adjustment vs Stable	•													•				
	Boundary Adjustment vs Width Adjustment	•																•	
	Boundary Adjustment vs Stable	•																	
	Width Adjustment vs Stable										•				•				
	SUM	*12*					*1*	*3*		*12*	*4*		*1*	*5*	*3*		*1*	*10*	*9*

Table C.7. Statistically significant differences (p value <0.005) between planform adjustments, stable reaches, geomorphic variables, channel stream order and catchment for valley bottom width. Dots indicate the presence of statistically significant differences.

Valley bottom width		BASSENTHWAITE	CALDER	CALDEW	CALDER	CAWDALE	CONISTON	CRUMMOCK	DUDDON	ENNERDALE	ESK	HAWESWATER	KENT	SLEDDALE	SPRINT	SWINDALE	ULLSWATER	WASDALE	WINDERMERE
STREAM ORDER 2	Bar Adjustment vs Bend Adjustment	•							•										•
	Bar Adjustment vs Boundary Adjustment																		
	Bar Adjustment vs Width Adjustment									•									
	Bar Adjustment vs Stable											•					•		
	Bend Adjustment vs Width Adjustment																		
	Bend Adjustment vs Boundary Adjustment																		
	Bend Adjustment vs Stable	•							•										•
	Boundary Adjustment vs Width Adjustment																		
	Boundary Adjustment vs Stable															•			
	Width Adjustment vs Stable									•									
STREAM ORDER 3	Bar Adjustment vs Bend Adjustment		•								•	•							
	Bar Adjustment vs Boundary Adjustment							•										•	
	Bar Adjustment vs Width Adjustment							•		•	•	•							
	Bar Adjustment vs Stable									•	•	•						•	
	Bend Adjustment vs Width Adjustment							•										•	•
	Bend Adjustment vs Boundary Adjustment									•									
	Bend Adjustment vs Stable		•								•	•							
	Boundary Adjustment vs Width Adjustment																	•	
	Boundary Adjustment vs Stable		•					•		•									•
	Width Adjustment vs Stable							•		•	•	•						•	
STREAM ORDER 4	Bar Adjustment vs Bend Adjustment														•				
	Bar Adjustment vs Boundary Adjustment																	•	
	Bar Adjustment vs Width Adjustment																		
	Bar Adjustment vs Stable																		
	Bend Adjustment vs Width Adjustment																	•	
	Bend Adjustment vs Boundary Adjustment																		
	Bend Adjustment vs Stable														•				
	Boundary Adjustment vs Width Adjustment																	•	
	Boundary Adjustment vs Stable																	•	
	Width Adjustment vs Stable																		
	SUM	2	3					5	2	7	5	6			2	1	1	9	4

Table C.8. Statistically significant differences (p value <0.005) between planform adjustments, stable reaches, geomorphic variables, channel stream order and catchment for specific stream power. Dots indicate the presence of statistically significant differences.

Specific Stream Power		BASSENTHWAITE	CALDER	CALDEW	CALDER	CAWDALE	CONISTON	CRUMMOCK	DUDDON	ENNERDALE	ESK	HAWESWATER	KENT	SLEDDALE	SPRINT	SWINDALE	ULLSWATER	WASDALE	WINDERMERE
STREAM ORDER 2	Bar Adjustment vs Bend Adjustment	•									•			•					
	Bar Adjustment vs Boundary Adjustment											•							
	Bar Adjustment vs Width Adjustment																		
	Bar Adjustment vs Stable	•										•	•				•		•
	Bend Adjustment vs Width Adjustment										•								
	Bend Adjustment vs Boundary Adjustment												•						
	Bend Adjustment vs Stable										•								
	Boundary Adjustment vs Width Adjustment																		
	Boundary Adjustment vs Stable																		
	Width Adjustment vs Stable									•									
STREAM ORDER 3	Bar Adjustment vs Bend Adjustment	•													•				
	Bar Adjustment vs Boundary Adjustment																		
	Bar Adjustment vs Width Adjustment	•								•				•					
	Bar Adjustment vs Stable									•	•	•							•
	Bend Adjustment vs Width Adjustment																		
	Bend Adjustment vs Boundary Adjustment	•								•				•					
	Bend Adjustment vs Stable	•			•						•	•							
	Boundary Adjustment vs Width Adjustment	•																	
	Boundary Adjustment vs Stable																		
	Width Adjustment vs Stable	•								•				•					
STREAM ORDER 4	Bar Adjustment vs Bend Adjustment														•		•		
	Bar Adjustment vs Boundary Adjustment								•									•	
	Bar Adjustment vs Width Adjustment																		
	Bar Adjustment vs Stable																		
	Bend Adjustment vs Width Adjustment																		
	Bend Adjustment vs Boundary Adjustment																		
	Bend Adjustment vs Stable														•		•		
	Boundary Adjustment vs Width Adjustment																		
	Boundary Adjustment vs Stable								•										
	Width Adjustment vs Stable																		
	SUM	*8*			*1*				*2*	*5*	*5*	*4*	*2*	*4*	*3*		*3*	*1*	*2*

References

Ackers, P., Charlton, F.G., 1970. Meander geometry arising from varying flows. Journal of Hydrology 11, 230–252.

Alber, A., Piégay, H., 2011. Spatial disaggregation and aggregation procedures for characterizing fluvial features at the network-scale: Application to the Rhône basin (France). Geomorphology, 125(3), 343-360.

Allaby, M., 1983. The changing uplands. Countryside Commission, Cheltenham.

Allen, J.R.L., 1965. A review of the origin and characteristics of recent alluvial sediments. Sedimentology, 5(2), 89-191.

Anderson, M.G., Calver, A., 1977. On the persistence of landscape features formed by a large flood. Transactions of the Institute of British Geographers, 243–254.

Anderson, M.G., Calver, A., 1980. Channel plan changes following large floods. In: Cullingford R.A., Davidson D.A., Lewin J. (Eds.), Timescales in geomorphology. Wiley Chichester, 43-52.

Anderton, J., Haworth, E.Y., Horne, D.J., Wray, D.S., 1998. Environmental impacts of lead mining in the Ullswater catchment (English Lake District): dam failures and flooding. In: Bennett, M.R., Doyle, P. (Eds.), Issues in Environmental Geology: A British Perspective. Geological Society of London, 226–242.

Archer, D.R., 2003. The rape of the Tyne: gravel extraction. In: Archer, D.R. (Ed.), Tyne and Tide: A Celebration of the River Tyne. Daryan Press, Ovingham, Northumberland, 44–58.

Ashbridge, D., 1995. Processes of river bank erosion and their contribution to the suspended sediment load of the River Culm, Devon. In: Foster I., Gurnell A., Webb B. (Eds.), Sediment and water quality in river catchments. John Wiley and Sons, Chichester, 229-245.

Ashworth, P. J., & Ferguson, R. I., 1986. Interrelationships of channel processes, changes and sediments in a proglacial braided river. Geografiska Annaler: Series A, Physical Geography, 68(4), 361–371.

Atherden, M., 1992. Upland Britain: a natural history. Manchester University Press.

Averis, A.M., Averis, A.B.G., Birks, H.J.B., Horsfield, D., Thompson, D.B.A., Yeo, M.J.M., 2004. Illustrated guide to British upland vegetation, Joint Nature Conservation Committee. Pelagic Publishing, Exeter.

Bagnold, R.A., 1966. An approach to the sediment transport problem from general physics. Geological Survey Proffessional Paper 422-I. United States Government Printing Office, Washington. 1-24.

Baker, V., Costa, J., 1987. Flood power. In: Mayer L., Nash D. (Eds.), Catastrophic Flooding. Allen and Unwin, Boston, 1-20.

Barker, P.A., Wilby, R.L., Borrows, J., 2004. A 200-year precipitation index for the central English Lake District. Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 49, 769–785.

BBC, 2016. Flood-hit A591: Closure 'to cost Lake District £1m a day'. http://www.bbc.co.uk/news/uk-england-cumbria-35547704

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., Roni, P., Pollock, M.M., 2010. Process-based principles for restoring river ecosystems. BioScience 60, 209–222.

Benda, L., Poff, N.L., Miller, D., Dunne, T., Reeves, G., Pess, G., Pollock, M., 2004. The network dynamics hypothesis: How channel networks structure riverine habitats. BioScience 54, 413–427.

Bertrand, M. and Liébault, F., 2019. Active channel width as a proxy of sediment supply from mining sites in New Caledonia. Earth Surface Processes and Landforms, 44(1), pp.67-76.

Bickerdike, H.L., Evans, D.J.A., Ó Cofaigh, C., Stokes, C.R., 2016. The glacial geomorphology of the Loch Lomond Stadial in Britain: a map and geographic information system resource of published evidence. Journal of Maps 12, 1178–1186.

Bizzi, S., Lerner, D.N., 2012. Characterizing physical habitats in rivers using map-derived drivers of fluvial geomorphic processes. Geomorphology, 169, 64-73.

Bizzi, S., Piégay, H., Demarchi, L., Van de Bund, W., Weissteiner, C., Gob, F., 2019. LiDAR-based fluvial remote sensing to assess 50–100-year human-driven channel changes at a regional level: The case of the Piedmont Region, Italy. Earth Surface Processes and Landforms, 44(2), 471-489.

Black, A.R., Law, F.M., 2004. Development and utilization of a national web-based chronology of hydrological events/Développement et utilisation sur internet d'une chronologie nationale d'événements hydrologiques. Hydrological Sciences Journal, 49(2), 237-246.

Blacknell, C., 1981. River erosion in an upland catchment. Area 39–44.

Boardman, J., 1988. Classic landforms of the Lake District. The Geographical Association, Sheffield.

Boulton, G.S., Jones, A.S., Clayton, K.M., Kenning, M.J., 1977. British ice-sheet model and patterns of glacial erosion and deposition in Britain, in: Shotten, F.W. (Ed.), British Quaternary Studies; Recent Advances. Claredon Press, Oxford. 231–246.

Bowes, P.L., Proud, W.N., 1984. Weardale dams and water courses. "The Bonny Moor Hen". Journal of the Weardale Field Study Society 3, 16–22.

Bracken, L.J., Turnbull, L., Wainwright, J., Bogaart, P., 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. Earth Surface Processes and Landforms, 40(2), 177-188.

Bravard, J., Amoros, C., Pautou, G., Bornette, G., Bournaud, M., Creuzé des Châtelliers, M., Gibert, J., Peiry, J., Perrin, J., Tachet, H., 1997. River incision in south-east France: morphological phenomena and ecological effects. Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management 13, 75–90.

Brewer, P.A. and Lewin, J., 1998. Planform cyclicity in an unstable reach: complex fluvial response to environmental change. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Group, 23(11), 989-1008.

Brewer, P.A., Maas, G.S., Macklin, M.G., 2000. A fifty-year history of exposed riverine sediment dynamics on Welsh rivers. BHS Occasional Paper 11, 245–252.

Brewer, P.A., Passmore, D.G., 2002. Sediment budgeting techniques in gravel-bed rivers. Geological Society, London, Special Publications, 191(1), 97-113.

Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publishing, Oxford.

Brierley, G.J., Fryirs, K.A., 2016. The Use of Evolutionary Trajectories to Guide "Moving Targets" in the Management of River Futures. River Research and Applications 32, 823–835.

British Geological Survey., 2016. British Geological Survey 50 k superficial deposits and bedrock geology. Source: https://www.bgs.ac.uk/products/digitalmaps/DiGMapGB_50.html

Bromley, J., 2015. Thirlmere Catchment Sediment Management Plan, United Utilities, Warrington.

Brookes, A., 1985. Traditional engineering methods, physical consequences and alternative practices. Progress in Physical Geography, 9, 44–73.

Brookes, A., 1987. River channel adjustments downstream from channelization works in England and Wales. Earth Surface Processes and Landforms, 12, 337–351.

Brookes, A., 1988. Channelized rivers: perspectives for environmental management. John Wiley & Sons, Guildford.

Brookes, A., 1995. Challenges and Objectives for Geomorphology in UK River Management. Earth Surface Processes and Landforms, 20, 593–610.

Brookes, A., Gregory, K.J., Dawson, F.H., 1983. An assessment of river channelization in England and Wales. Science of the Total Environment 27, 97–111.

Brown, A.G., 1997. Alluvial Geoarchaeology: Floodplain Archaeology and Environmental Change. Cambridge University Press, Cambridge.

Brown, A.G., Tooth, S., Bullard, J.E., Thomas, D.S.G., Chiverrell, R.C., Plater, A.J., Murton, J., Thorndycraft, V.R., Tarolli, P., Rose, J., Wainwright, J., Downs, P., Aalto, R., 2017. The geomorphology of the Anthropocene: emergence, status and implications. Earth Surface Processes and Landforms 42, 71–90.

Brown, V., 2009. Reconstructing Loch Lomond Stadial glaciers and climate in the south-west English Lake District. Department of Geography. Durham University.

Brunsden, D., Thornes, J., 1979. Landscape sensitivity and change. T I Brit Geogr, 463-484.

Bull, W. B., 1991. Geomorphic Responses to Climatic Change, Oxford University Press, New York.

Burt, T., Allison, R.J., 2010. Sediment cascades: an integrated approach. John Wiley and Sons, Chichester.

Busby, J.P., Merritt, J.W., 1999. Quaternary deformation mapping with ground penetrating radar. Journal of Applied Geophysics 41, 75–91.

Butler, D.R., Malanson, G.P., 1993. An unusual early-winter flood and its varying geomorphic impact along a subalpine river in the Rocky Mountains. Z. Geomorph., 37 (2), 145-155

Caine, N., Swanson, F., 2013. Geomorphic coupling of hillslope and channel systems in two small mountain basins. In: Slaymaker O. (Ed.), Geomorphology: Critical Concepts in Geography. Routledge, Oxon, 159-173.

Carling, P., 1987. Bed stability in gravel streams, with reference to stream regulation and ecology. River channels: environment and process. Blackwell Scientific Publications, Oxford, 321-347.

Carling, P., 1988. The concept of dominant discharge applied to two gravel-bed streams in relation to channel stability thresholds. Earth Surface Processes and Landforms, 13(4), 355-367.

Carling, P., 1997. Sedimentology of the 1749 flood deposit. Geomorphology of the Lake District: a field guide, 23-29.

Carling, P., Glaister, M.S., 1987. Reconstruction of a flood resulting from a moraine-dam failure using geomorphological evidence and dam-break modeling, (UK). In: Mayer, L., Nash,D., (Eds.) Catastrophic flooding: Winchester, Mass., Allen and Unwin, 9, 181 – 200.

Carling, P.A., 1986. The Noon Hill flash floods; July 17th 1983. Hydrological and geomorphological aspects of a major formative event in an upland landscape. Transactions of the Institute of British Geographers 105–118.

CEH, 2015. North West Floods - Hydrological Update. https://www.ceh.ac.uk/news-and-media/blogs/north-west-floods-hydrological-update.

Chappell, J., 1983. Thresholds and lags in geomorphologic changes. The Australian Geographer 15, 357–366.

Chiverrell, R.C., 2006. Past and future perspectives upon landscape instability in Cumbria, northwest England. Regional Environmental Change 6, 101–114.

Chiverrell, R.C., Sear, D.A., Warburton, J., Macdonald, N., Schillereff, D.N., Dearing, J.A., Croudace, I.W., Brown, J. and Bradley, J., 2019. Using lake sediment archives to improve understanding of flood magnitude and frequency: recent extreme flooding in northwest UK. Earth Surface Processes and Landforms. 44(12), 2366-2376.

Chorley, R.J., Kennedy, B.A., 1971. Physical Geography: A Systems Approach. Prentice-Hall International, London.

Chow, T.V., 1959. Open-channel Hydraulics. McGraw-Hill Inc., New York.

Church, M. Rice, S.P., 2009. Form and growth of bars in a wandering gravel-bed river. Earth Surface Processes and Landforms, 34(10), 1422-1432.

Church, M., 1996. Channel morphology and typology, in: Petts, G.E., Carlow, P. (Eds.), River Flows and Channel Forms: Selected Extracts from the Rivers Handbook. Blackwell Science, Oxford, 186-202.

Church, M., 2002. Geomorphic thresholds in riverine landscapes. Freshwater Biology., 47 (4), 541-557.

Church, M., Ashmore, P., 1998. Sediment transport and river morphology: a paradigm for study. In Gravel-Bed Rivers in the Environment, Klingeman PC (ed). Water Resources Centre: Highlands Ranch, CO.

Church, M., Jones, D., 1982. Channel bars in gravel-bed rivers. Gravel-bed rivers: Fluvial Processes, Engineering and management. John Wiley and Sons, Chichester, 291-338.

Cienciala, P., Nelson, A.D., Haas, A.D., Xu, Z., 2020. Lateral geomorphic connectivity in a fluvial landscape system: Unraveling the role of confinement, biogeomorphic interactions, and glacial legacies. Geomorphology, 354, 107036.

Constantine, J.A., Dunne, T., Ahmed, J., Legleiter, C., Lazarus, E.D., 2014. Sediment supply as a driver of river meandering and floodplain evolution in the Amazon Basin. Nature Geoscience 7, 899–903.

Cooper, A.H., Rushton, A.W.A., Molyneux, S.G., Hughes, R.A., Moore, R.M., Webb, B.C., 1995. The stratigraphy, correlation, provenance and palaeogeography of the Skiddaw Group (Ordovician) in the English Lake District. Geological Magazine 132, 185–211.

Coulthard, T.J., Macklin, M.G., 2001. How sensitive are river systems to climate and land-use changes? A model-based evaluation. Journal of Quaternary Science 16, 347–351.

Crosato, A., Saleh, M.S., 2011. Numerical study on the effects of floodplain vegetation on river planform style. Earth Surface Processes and Landforms 36, 711–720.

Crozier, M.J., 2010. Landslide geomorphology: an argument for recognition, with examples from New Zealand. Geomorphology, 120(1-2), 3-15.

Cumberland River Board., (1950 – 1965). Annual Reports 1950 - 1965. River Board House, Carlisle, Cumberland.

Cumbria County Council., 2008. Cumbria Climate Change Strategy. Carlisle. https://www.copeland.gov.uk/sites/default/files/attachments/cumbclimatechangestrat08_12.pdf

Curran, J.H., Wohl, E.E., 2003. Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. Geomorphology 51 (1–3), 141.

Darby, S.E., Thorne, C.R., 1992. Impact of channelization on the Mimmshall Brook, Hertfordshire, UK. Regulated Rivers: Research & Management 7, 193–204.

David, M., Labenne, A., Carozza, J.M. and Valette, P., 2016. Evolutionary trajectory of channel planforms in the middle Garonne River (Toulouse, SW France) over a 130-year period: Contribution of mixed multiple factor analysis (MFAmix). Geomorphology, 258, 21-39.

Davies, G., Turner, J., 1979. Pollen diagrams from Northumberland. New Phytologist 82, 783–804.

Davies, T.R., Korup, O., 2010. Sediment Cascades in Active Landscapes. In: Burt T., Allison R.J. (Eds.), Sediment Cascades: An Integrated Approach. John Wiley and Sons, Chichester, 89-115.

Dietrich, W.E., Dunne, T., 1978. Sediment budget for a small catchment in a mountainous terrain. Z. Geomorph. 29, 191 – 206.

Digimap, 2017. EDINA Digimap Data Collection. https://digimap.edina.ac.uk/

Dixon, H., Lawler, D.M., Shamseldin, A.Y., Webster, P., 2006. The effect of record length on the analysis of river flow trends in Wales and central England. IAHS-AISH publication, 490–495.

Donovan, M., Belmont, P., Notebaert, B., Coombs, T., Larson, P. and Souffront, M., 2019. Accounting for uncertainty in remotely-sensed measurements of river planform change. Earth-science reviews. 193, 220-236.

Donovan, M., Miller, A., Baker, M. and Gellis, A., 2015. Sediment contributions from floodplains and legacy sediments to Piedmont streams of Baltimore County, Maryland. Geomorphology, 235, 88-105.

Downs, P.W., 1994. Characterization of river channel adjustments in the Thames basin, south-east England. Regulated Rivers: Research & Management, 9(3), 151-175.

Downs, P.W., 1995. Estimating the probability of river channel adjustment. Earth Surface Processes and Landforms, 20(7), 687-705.

Downs, P.W., Gregory, K.J., 1993. The sensitivity of river channels in the landscape system, in: Thomas, D.S.G., Allison, R.J. (Eds.), Landscape Sensitivity. Wiley, Chichester, 15–30.

Downs, P.W., Gregory, K.J., 2004. River channel management: towards sustainable catchment hydrosystems. Arnold, London.

Downs, P.W., Piégay, H., 2019. Catchment-scale cumulative impact of human activities on river channels in the late Anthropocene: implications, limitations, prospect. Geomorphology 338, 88–104.

Downward, S., Gurnell, A., Brookes, A., 1994. A methodology for quantifying river channel planform change using GIS. IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences, 224, 449-456.

Du Boys, M., 1879. The Rhone and streams with movable beds. Annals des Pontes et Chaussees, 18, 141-195.

Dufour, S., Piégay, H., 2009. From the myth of a lost paradise to targeted river restoration: Forget natural references and focus on human benefits. River Research and Applications 25, 568–581.

Durand, M., Gleason, C.J., Garambois, P.A., Bjerklie, D., Smith, L.C., Roux, H., Rodriguez, E., Bates, P.D., Pavelsky, T.M., Monnier, J. and Chen, X., 2016. An inter comparison of remote sensing river discharge estimation algorithms from measurements of river height, width, and slope. Water Resources Research, 52(6), 4527-4549.

Dury, G.H., 1961. Bankfull discharge: an example of its statistical relationships. Hydrol. Sci. J. 6 (3), 48–55.

Dury, G.H., 1964. Principles of underfit streams (Vol. 452). US Government Printing Office.

Dury, G.H., 1997. STREAMS---UNDERFITStreams---underfit, in: Geomorphology. Springer Berlin Heidelberg, Berlin, Heidelberg, 1070–1071.

Edina Digimap., 2016. EDINA Digimap Data Collection. https://digimap.edina.ac.uk/

Edwards, K.J., Whittington, G., 2001. Lake sediments, erosion and landscape change during the Holocene in Britain and Ireland. Catena 42, 143–173.

England, J., Gurnell, A.M., 2016. Incorporating catchment to reach scale processes into hydromorphological assessment in the UK. Water and Environment Journal, 30(1-2), 22-30.

Environment Agency. 2005. Fluvial Audit: A method for Catchment-scale Geomorphological Assessment. Method Description (Report A). Babtie Brown & Root No. BWA 0009137. 32pp.

Environment Agency. 2006. Cumbria floods technical report. Factual report on meteorology, hydrology and impacts of the January 2005 flooding in Cumbria. http://www.bramptonweather.co.uk/data/CarlisleFloods2005.pdf

Environment Agency., 2018. Estimating the economic costs of the 2015 to 2016 winter floods. Bristol.

Environment Agency., 2019. Assessment Management Data: spatial flood defences, maintenance programme, capital investment programme and completed schemes: https://environment.data.gov.uk/asset-management/

Environment Agency., 2019b. River Habitat Survey – Survey Details and Summary Results. https://data.gov.uk/dataset/4cb467c9-346e-44ac-85c6-6cd579111e2c/river-habitat-survey-survey-details-and-summary-results#licence-info

Erskine, W.D., Geary, P.M., Outhet, D.N., 1985. Potential impacts of sand and gravel extraction on the Hunter River, New South Wales. Australian Geographical Studies 23, 71–86.

European Commission, 2007. European Commission Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood Risks. Official Journal of the European Communities L 288/27.

European Commission. 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities L327, 1–72.

Evans, D.J.A., McDougall, D., 2015. Bedrock geology and physiography. In: McDougall, D., Evans, D.J.A., (Eds.) The Quaternary of the Lake District: Field Guide. Quaternary Research Association, London, 1-9.

Evans, M., Warburton, J., 2001. Transport and dispersal of organic debris (peat blocks) in upland fluvial systems. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group 26, 1087–1102.

Evans, M., Warburton, J., Yang, J., 2006. Eroding blanket peat catchments: global and local implications of upland organic sediment budgets. Geomorphology 79, 45–57.

Evans, R., 1990. Soils at risk of accelerated erosion in England and Wales. Soil use and Management 6, 125–131.

Evans, R., 1997. Soil erosion in the UK initiated by grazing animals: a need for a national survey. Applied Geography 17, 127–141.

Ferguson, R.I., 1977. Meander migration: equilibrium and change. River channel changes, 235-248.

Ferguson, R.I., 1981. Channel forms and channel changes. In: Lewin J. (Ed.), British Rivers. George Allen and Unwin, London, 90-125.

Ferguson, R.I., 1987. Hydraulic and sedimentary controls of channel pattern, in: Richards, K.S. (Ed.), River Channels: Environments and Processes. Blackwell, Oxford, 129–158.

Fortey, N.J., Roberts, B., Hirons, S.R., 1993. Relationship between metamorphism and structure in the Skiddaw Group, English Lake District. Geological Magazine 130, 631–638.

Foster, I.D.L., 2010. Lakes and Reservoirs in the SedimentCcascade, in: Burt, T., Allison, R.J. (Eds.), Sediment Cascades: An Integrated Approach. John Wiley and Sons, Chichester, 345–376.

Foulds, S.A., Macklin, M.G., 2016. A hydrogeomorphic assessment of twenty-first century floods in the UK. Earth Surface Processes and Landforms 21, 256–270.

Fryer, G., 1991. A natural history of the lakes, tarns and streams of the English Lake District. Freshwater Biological Association, Cumbria.

Fryirs, K.A., 2013. (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. Earth Surface Processes and Landforms, 38(1), 30-46.

Fryirs, K.A., Brierley, G.J., 2010. Antecedent controls on river character and behaviour in partly confined valley settings: Upper Hunter catchment, NSW, Australia. Geomorphology, 117(1-2), 106-120.

Fryirs, K.A., Brierley, G.J., 2012. Geomorphic analysis of river systems: an approach to reading the landscape. John Wiley & Sons, Chichester.

Fryirs, K.A., Brierley, G.J., 2016. Assessing the geomorphic recovery potential of rivers: forecasting future trajectories of adjustment for use in management. Wiley Interdisciplinary Reviews: Water, 3(5), 727-748.

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M., 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. Catena, 70(1), 49-67.

Fryirs, K.A., Spink, A., Brierley, G., 2009. Post-European settlement response gradients of river sensitivity and recovery across the upper Hunter catchment, Australia. Earth Surface Processes and Landforms, 34(7), 897-918.

Fryirs, K.A., Wheaton, J.M., Brierley, G.J., 2016. An approach for measuring confinement and assessing the influence of valley setting on river forms and processes. Earth Surface Processes and Landforms, 41(5), 701-710.

Fuller, I., Passmore, D., Heritage, G., Large, A., Milan, D., Brewer, P., 2002. Annual sediment budgets in an unstable gravel-bed river: the River Coquet, northern England. Geological Society, London, Special Publications, 191(1), 115-131.

Fuller, I.C., 2007. Geomorphic work during a "150-year" storm: contrasting behaviors of river channels in a New Zealand catchment. Ann. Assoc. Am. Geogr. 97 (4), 665–676.

Fuller, I.C., 2008. Geomorphic impacts of a 100-year flood: Kiwitea Stream, Manawatu catchment, New Zealand. Geomorphology, 98(1-2), 84-95.

Fuller, I.C., Gilvear, D.J., Thoms, M.C. and Death, R.G., 2019b. Framing resilience for river geomorphology: Reinventing the wheel? River research and applications, 35(2), 91-106.

Fuller, I.C., Large, A.R.G., Charlton, M.E., Heritage, G.L., Milan, D.J., 2003. Reach-scale sediment transfers: An evaluation of two morphological budgeting approaches. Earth Surface Processes and Landforms, 28(8), 889-903.

Fuller, I.C., Macklin, M.G., Toonen, W.H., Turner, J. and Norton, K., 2019. A 2000 year record of palaeofloods in a volcanically-reset catchment: Whanganui River, New Zealand. Global and Planetary Change,181,102981, 1-12.

Fuller, I.C., Riedler, R.A., Bell, R., Marden, M. and Glade, T., 2016. Landslide-driven erosion and slope–channel coupling in steep, forested terrain, Ruahine Ranges, New Zealand, 1946–2011. Catena, 142, 252-268.

Gardiner, J.L., 1990. River projects and conservation: a manual for holistic appraisal. John Wiley and Sons Ltd.

Gellis, A.C., Myers, M.K., Noe, G.B., Hupp, C.R., Schenk, E.R., Myers, L., 2017. Storms, channel changes, and a sediment budget for an urban-suburban stream, Difficult Run, Virginia, USA. Geomorphology, 278, 128-148.

Gergel, S.E., Dixon, M.D., Turner, M.G., 2002. Consequences of human-altered floods: levees, floods, and floodplain forests along the Wisconsin River Ecological Applications, 12(6), 1755-1770.

Gilvear, D., Bryant, R., 2016. Analysis of remotely sensed data for fluvial geomorphology and river science, Tools in Fluvial Geomorphology, 103 – 102.

Gilvear, D.J. and Winterbottom, S.J., 1992. Channel change and flood events since 1783 on the regulated River Tay, Scotland: implications for flood hazard management. Regulated Rivers: Research & Management, 7(3), 247-260.

Gilvear, D.J., 1993. River management and conservation issues on formerly braided river systems; the case of the River Tay, Scotland. Geological Society, London, Special Publications 75, 231–240.

Gilvear, D.J., 1999. Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework. Geomorphology 31, 229–245.

Gilvear, D.J., 2003. Spatial and temporal patterns of channel adjustment to impoundment on the Upper River Spey, Scotland (1942-2000). River Research and Applications 19, 34–49.

Gleason, C.J., Smith, L.C. and Lee, J., 2014. Retrieval of river discharge solely from satellite imagery and at-many-stations hydraulic geometry: Sensitivity to river form and optimization parameters. Water Resources Research, 50(12), 9604-9619.

Gordon, N., D, McMahon, T., A, Finlayson, B., L, 1992. Sediment Motion, Stream hydrology: an introduction for ecologists. John Wiley and Sons, Chichester, 324-336.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J., Nathan, R.J., 2004. Stream hydrology: an introduction for ecologists. John Wiley and Sons.

Grabowski, R.C., Gurnell, A.M., Burgess-Gamble, L., England, J., Holland, D., Klaar, M.J., Morrissey, I., Uttley, C. and Wharton, G., 2019. The current state of the use of large wood in river restoration and management. Water and Environment Journal, 33(3), 366-377.

Grabowski, R.C., Surian, N., Gurnell, A.M., 2014. Characterizing geomorphological change to support sustainable river restoration and management. Wiley Interdisciplinary Reviews: Water 1, 483–512.

Graf, W. L. (1984), A Probabilistic Approach to the Spatial Assessment of River Channel Instability, Water Resources Research, 20(7), 953– 962.

Grantham, R.B., 1859. On the arterial drainage and outfalls. Minutes and Proceedings of the Institute of Civil Engineers XIX, 53–130.

Grayson, R.P., Plater, A.J., 2009. A lake sediment record of Pb mining from Ullswater, English Lake District, UK. Journal of Paleolimnology 42, 183–197.

Gregory, K.J., 2019. Human influence on the morphological adjustment of river channels: The evolution of pertinent concepts in river science. River Research and Applications 35, 1097–1106.

Gregory, K.J., Gurnell, A.M., Hill, C.T., 1985. The permanence of debris dams related to river channel processes. Hydrological Sciences 30, 371–381.

Gurnell, A., 2014. Plants as river system engineers. Earth Surface Processes and Landforms 39, 4–25.

Gurnell, A., England, J., Burgess-Gamble, L., 2019. Trees and wood: working with natural river processes. Water and Environment Journal 33, 342–352.

Gurnell, A.M., 1983. Downstream channel adjustments in response to water abstraction for hydro-electric power generation from alpine glacial melt-water streams. The Geographical Journal, 149(3), 342-354.

Gurnell, A.M., del Tánago, M.G., Rinaldi, M., Grabowski, R., Henshaw, A., O'Hare, M., Belletti, B., Buijse, A.D., 2015. Development and application of a multi-scale process-based framework for the hydromorphological assessment of European rivers, in: Engineering Geology for Society and Territory-Volume 3. Springer, 339–342.

Gurnell, A.M., Peiry, J.L. and Petts, G.E., 2003. Using historical data in fluvial geomorphology. Tools in fluvial geomorphology, 77-101.

Gurnell, A.M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, A.D., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., García de Jalón, D., González del Tánago, M., Grabowski, R.C., Gunn, I.D.M., Habersack, H., Hendriks, D., Henshaw, A.J., Klösch, M., Lastoria, B., Latapie, A., Marcinkowski, P., Martínez-Fernández, V., Mosselman, E., Mountford, J.O., Nardi, L., Okruszko, T., O'Hare, M.T., Palma, M., Percopo, C., Surian, N., van de Bund, W., Weissteiner, C., Ziliani, L., 2016. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquatic Sciences, 78(1), 1-16.

Gurnell, A.M., Sweet, R., 1998. The distribution of large wood accumulations and pools in relation to woodland stream management in a small, low-gradient stream. Earth Surface Processes and Landforms 23, 1101–1121.

Hall, J.E., Holzer, D.M., Beechie, T.J., 2007. Predicting river floodplain and lateral channel migration for salmon habitat conservation. Journal of the American Water Resources Association, 43(3), 786-797.

Harkness, D.D., Miller, B.F., Tipping, R.M., 1997. NERC radiocarbon measurements 1977–1988. Quaternary Science Reviews 16, 925–927.

Harley, J.B., 1965a. The re-mapping of England, 1700 - 1800. Imago Mundi, 19, 56 - 67.

Harley, J.B., 1965b. The re-mapping of England, 1750–1800. The International Journal for the History of Cartography 19, 56–67.

Harley, J.B., 1972. Maps for the local historian: a guide to the British sources. National Council of Social Service, London.

Harley, J.B., 1975. The Ordnance Survey Maps, a Descriptive Manual. Ordnance Survey, Southampton, pp. 200.

Harvey, A., 1997. Fluvial geomorphology of north-west England. In: Gregory K.J. (Ed.), Fluvial Geomorphology of Great Britain. Geological Conservation Review Series. Chapman & Hall London, 173-200.

Harvey, A.M., 1977. Event frequency in sediment production and channel change. River Channel Change, New York, John Wiley and Sons. 20, 301 - 310.

Harvey, A.M., 1986. Geomorphic effects of a 100 year storm in the Howgill Fells, Northwest England. Zeitschrift Fur Geomorphologie 30, 71–91.

Harvey, A.M., 1991. The influence of sediment supply on the channel morphology of upland streams: Howgill Fells, Northwest England. Earth Surface Processes and Landforms 16, 675–684.

Harvey, A.M., 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. Catena, 42(2-4), 225-250.

Harvey, A.M., 2007. Differential recovery from the effects of a 100-year storm: Significance of long-term hillslope–channel coupling; Howgill Fells, northwest England. Geomorphology, 84(3–4), 192-208.

Hatfield, R.G., Maher, B.A., 2009a. Fingerprinting upland sediment sources: particle size-specific magnetic linkages between soils, lake sediments and suspended sediments. Earth Surface Processes and Landforms 34, 1359–1373.

Hatfield, R.G., Maher, B.A., 2009b. Holocene sediment dynamics in an upland temperate lake catchment: climatic and land-use impacts in the English Lake District. The Holocene 19, 427–438.

Hay, T., 1926. Delta formation in the English Lakes. Geological Magazine, 63, 292-301.

Heckmann, T., Haas, F., Abel, J., Rimbock, A., Becht, M., 2017. Feeding the hungry river: Fluvial morphodynamics and the entrainment of artificially inserted sediment at the dammed river Isar, Eastern Alps, Germany. Geomorphology 291, 128–142.

Heckmann, T., Schwanghart, W., Phillips, J.D., 2015. Graph theory—Recent developments of its application in geomorphology. Geomorphology, 243, 130-146.

Herdendorf, C.E., 1982. Large lakes of the world. Journal of Great Lakes Research, 8(3), 379-412.

Heritage, G. and Entwistle, N., 2019. Drone Based Quantification of Channel Response to an Extreme Flood for a Piedmont Stream. Remote Sensing, 11(17), 1-16.

Heritage, G.L., Entwistle, N.S., Milan, D.J., 2019. Evidence of non-contiguous flood driven coarse sediment transfer and implications for sediment management, in: 38th IAHR World Congress 1-6th September, 2019. Panama, pp. 113–120.

Hey, R., Winterbottom, A., 1990. River engineering in National Parks: the case of the River Wharfe, UK. Regulated Rivers: Research & Management, 5(1), 35-44.

Hey, R.D., 1975. Design discharge for natural channels In: Hey R.D., Davies J.D. (Eds.), Science Technology and Environmental Management. Saxon House, Farnborough, 71-81.

Hey, R.D., 1979. Dynamic process-response model of river channel development. Earth Surface Processes, 4(1), 59-72.

Hey, R.D., Thorne, C.R., 1986. Stable channels with mobile gravel beds. Journal of Hydraulic Engineering 112, 671–689.

Hickin, E.J., 1978. Mean flow structure in meanders of the Squamish River, British Columbia. Canadian Journal of Earth Sciences, 15(11), 1833-1849.

Hickin, E.J., 1984. Vegetation and river channel dynamics. Canadian Geographer/Le Géographe canadien 28, 111–126.

Higgitt, D.L., Warburton, J., Evans, M.G., 2001. Sediment transfer in upland environments. In: Higgitt D.L., Lee M.E. (Eds.), Geomorphological processes and landscape change: Britain in the last 1000 years. Blackwell Publishers Ltd, Oxford, UK, 190-214.

Hinderer, M., 2012. From gullies to mountain belts: A review of sediment budgets at various scales. Sediment Geol., 280, 21-59.

Hindle, B.P., 1984. Roads and Trackways of the Lake District. Moorland, Leeds.

Hoey, T., 1992. Temporal variations in bedload transport rates and sediment storage in gravel-bed rivers. Progress in Physical Geography 16, 319–338.

Hooke, J.M., 1977. The distribution and nature of changes in river channel patterns: The example of Devon. In: Gregory K.J. (Ed.), River Channel Changes. John Wiley & Sons, Chichester, 265-280.

Hooke, J.M., 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. Geomorphology, 56(1), 79-94.

Hooke, J.M., 2019. Changing landscapes: Five decades of applied geomorphology. Geomorphology. https://doi.org/10.1016/j.geomorph.2019.06.007

Hooke, J.M., Redmond, C.E., 1989a. River-Channel Changes in England and Wales. Journal of the Institution of Water and Environmental Management 3, 328–335.

Hooke, J.M., Redmond, C.E., 1989b. Use of cartographic sources for analysing river channel change with examples from Britain, in: Historical Change of Large Alluvial Rivers: Western Europe. John Wiley & Sons, New York, 79–93.

Hooke, J.M., Yorke, L., 2010. Rates, distributions and mechanisms of change in meander morphology over decadal timescales, River Dane, UK. Earth Surface Processes and Landforms, 35(13), 1601-1614.

Horton, R.E., 1932. Drainage-basin characteristics. Eos, transactions american geophysical union 13, 350–361.

Horton, R.E., 1945. Erosional Development of Streams and Their Drainage Basins: Hydro-Physical Approach to Quantitative Morphology. Geological Society of American Bulletin, 56, 275-370.

Huddleston, F., 1935. The Floods of the Lake District, Part One. Penrith.

Hughes, M.L., McDowell, P.F., Marcus, W.A., 2006. Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. Geomorphology, 74(1-4), 1-16.

Hughes, R.M., Kaufmann, P.R. and Weber, M.H., 2011. National and regional comparisons between Strahler order and stream size. Journal of the North American Benthological Society, 30(1), 103-121.

Ibisate, A., Ollero, A., Diaz, E., 2011. Influence of catchment processes on fluvial morphology and river habitats. Limnetica, 30(2), 169-182.

Jackson, R.G., 1975. Hierarchical attributes and a unifying model of bed forms composed of cohesionless material and produced by shearing flow. Geological Society of America Bulletin, 86(11), 1523-1533.

James, L. A., & Lecce, S. A. (2013). Impacts of land-use and land-cover change on river systems. In E. Wohl (Ed.), Treatise on geomorphology, 9, 768–793. Elsevier, Amsterdam, Netherlands.

James, L.A., Hodgson, M.E., Ghoshal, S. and Latiolais, M.M., 2012. Geomorphic change detection using historic maps and DEM differencing: The temporal dimension of geospatial analysis. Geomorphology, 137(1), 181-198.

James, L.A., Marcus, W.A., 2006. The human role in changing fluvial systems: Retrospect, inventory and prospect. Geomorphology 79, 152–171.

Jang, C.-L., Shimizu, Y., 2007. Vegetation effects on the morphological behavior of alluvial channels. Journal of Hydraulic Research 45, 763–772.

Jeffries, R., 2002. 'The effect of woody vegetation on the geomorphology of a lowland floodplain: a study of a basin in southern England'. PhD thesis, University of Southampton. 270p.

Johnson, R., Warburton, J., Mills, A., 2008. Hillslope–channel sediment transfer in a slope failure event: Wet Swine Gill, Lake District, northern England. Earth Surface Processes and Landforms, 33(3), 394-413.

Johnson, R.M., Warburton, J., 2002. Flooding and geomorphic impacts in a mountain torrent: Raise Beck, Central Lake District, England. Earth Surface Processes and Landforms, 27(9), 945-969.

Johnson, R.M., Warburton, J., 2006. Variability in sediment supply, transfer and deposition in an upland torrent system: Iron Crag, northern England. Earth Surface Processes and Landforms, 31(7), 844-861.

Johnson, Richard M, Warburton, J., 2002b. Annual sediment budget of a UK mountain torrent. Geografiska Annaler: Series A, Physical Geography 84, 73–88.

Jones, A.F., Macklin, M.G. and Brewer, P.A., 2012. A geochemical record of flooding on the upper River Severn, UK, during the last 3750 years. Geomorphology, 179, 89-105.

Jones, L., Schumm, S., 1999. Causes of avulsion: an overview, Fluvial sedimentology VI. Spec. Publ. Int. Assoc. Sedimentol, 171-178.

Jones, P.D., Conway, D., 1997. Precipitation in the British Isles: an analysis of area-average data updated to 1995. International Journal of Climatology: A Journal of the Royal Meteorological Society 17, 427–438.

Joyce, H.M., Hardy, R.J., Warburton, J., Large, A.R.G., 2018. Sediment continuity through the upland sediment cascade: geomorphic response of an upland river to an extreme flood event. Geomorphology 317, 45–61.

Joyce, H.M., Warburton, J. and Hardy, R.J., 2020. A catchment scale assessment of patterns and controls of historic 2D river planform adjustment. Geomorphology, 354, 107046.

Kain, R.J. and Prince, H.C., 1985. The tithe surveys of England and Wales. Cambridge University Press. Cambridge.

Knighton, A.D., 1989. River adjustment to changes in sediment load: the effects of tin mining on the Ringarooma River, Tasmania, 1875–1984. Earth Surface Processes and Landforms 14, 333–359.

Knighton, A.D., 1998. Fluvial forms and processes: a new perspective. Arnold, London.

Knighton, A.D., 1999. Downstream variation in stream power. Geomorphology, 29(3-4), 293-306.

Knox, J.C., 2006. Floodplain sedimentation in the Upper Mississippi Valley: Natural versus human accelerated. Geomorphology, 79(3), 286-310.

Kondolf, G.M., 1997. PROFILE: hungry water: effects of dams and gravel mining on river channels. Environmental Management, 21(4), 533-551.

Kondolf, G.M., Matthews, W.V.G., 1991. Unmeasured Residuals in Sediment Budgets - a Cautionary Note. Water Resour Res, 27(9), 2483-2486.

Korup, O., 2005. Geomorphic imprint of landslides on alpine river systems, southwest New Zealand. Earth Surface Processes and Landforms, 30(7), 783-800.

Korup, O., 2012. Earth's portfolio of extreme sediment transport events. Earth-Science Reviews, 112(3-4), 115-125.

Kronvang, B., Svendsen, L.M., Brookes, A., Fisher, K., Møller, B., Ottosen, O., Newson, M., Sear, D., 1998. Restoration of the rivers Brede, Cole and Skerne: a joint Danish and British EU-LIFE demonstration project, III—channel morphology, hydrodynamics and transport of sediment and nutrients. Aquatic Conservation: Marine and Freshwater Ecosystems 8, 209–222.

Lancaster, S.T., Casebeer, N.E., 2007. Sediment storage and evacuation in headwater valleys at the transition between debris-flow and fluvial processes. Geology, 35(11), 1027-1030.

Lane, S.N., Reid, S.C., Tayefi, V., Yu, D., Hardy, R.J., 2008. Reconceptualising coarse sediment delivery problems in rivers as catchment-scale and diffuse. Geomorphology 98, 227–249.

Lane, S.N., Richards, K.S., 1997. Linking River Channel Form and Process: Time, Space and Causality Revisited. Earth Surface Processes and Landforms 22, 249–260.

Lane, S.N., Westaway, R.M. and Murray Hicks, D., 2003. Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 28(3), 249-271.

Langhammer, J., 2010. Analysis of the relationship between the stream regulations and the geomorphologic effects of floods. Natural hazards, 54(1), 121-139.

Lawler, D.M., 1993. The measurement of river bank erosion and lateral channel change: a review. Earth surface processes and landforms, 18(9), 777-821.

LDNPA, 2017. History and development of the English Lake District, in: LDNPA (Ed.), Nomination of the English Lake District. LDNPA, Cumbria, pp. 144–239.

Lea, D.M., Legleiter, C.J., 2016. Mapping spatial patterns of stream power and channel change along a gravel-bed river in northern Yellowstone. Geomorphology, 252, 66-79.

Lecce, S.A., 1997. Spatial patterns of historical overbank sedimentation and floodplain evolution, Blue River, Wisconsin. Geomorphology, 18(3-4), 265-277.

Lefrançois, J., Grimaldi, C., Gascuel-Odoux, C., Gilliet, N., 2007. Suspended sediment and discharge relationships to identify bank degradation as a main sediment source on small agricultural catchments. Hydrological Processes: An International Journal 21, 2923–2933.

Leopold, L.B. and Maddock, T., 1953. The hydraulic geometry of stream channels and some physiographic implications (Vol. 252). US Government Printing Office. 57.

Leopold, L.B. and Miller, J.P., 1956. Ephemeral streams: Hydraulic factors and their relation to the drainage net (Vol. 282). US Government Printing Office.

Leopold, L.B., Wolman, M.G., 1957. River Channel Patterns: Braided, Meandering and Straight. Geological Survey Professional Paper 282-B, Washington.

Lewin, J, Davies, B.E., Wolfenden, P.J., 1977a. Interactions between channel change and historic mining sediments. In: Gregory, K.J., (Ed.) River channel changes. John Wiley and Sons, Chichester. 23, 353–367.

Lewin, J., 1977. Channel pattern changes, in: Gregory, K.J. (Ed.), River Channel Changes. John Wiley & Sons, Chichester, New York, Brisbane, Toronto, 167–184.

Lewin, J., 1981. British Rivers. George Allen and Unwin, London.

Lewin, J., 1987. Historical river channel changes, in: Gregory, K.J., Lewin, J., Thornes, J.B. (Eds.), Palaeohydrology in Practice: A River Basin Analysis. John Wiley and Sons New York. 161-175,

Lewin, J., 2013. Enlightenment and the GM floodplain. Earth Surface Processes and Landforms, 38(1), 17-29.

Lewin, J., Bradley, S.B. and Macklin, M.G., 1983. Historical valley alluviation in mid-Wales. Geological Journal, 18(4), 331-350.

Lewin, J., Davies, B.E., Wolfenden, P.J., 1977b. Interactions between channel change and historic mining sediments. River channel changes 353–367.

Lewin, J., Hughes, D., 1976. Assessing channel change on Welsh rivers. Cambria, 3(1), 1-10.

Lewin, J., Hughes, D., Blacknell, C., 1977. Incidence of River Erosion. Area, 9(3), 177-180.

Lewin, J., Hughes, D., Blacknell, C., 1977. Incidence of river erosion. Area 177–180.

Lewin, J., Macklin, M.G., 1987. Metal mining and floodplain sedimentation in Brtain, in: Gardiner, V. (Ed.), International Geomorphology, Proceedings of the First Internaional Geomorphology Conference. Wiley, 1009–1027.

Lisenby, P.E., Croke, J. and Fryirs, K.A., 2018. Geomorphic effectiveness: a linear concept in a non-linear world. Earth Surface Processes and Landforms, 43(1), 4-20.

Lisenby, P.E., Fryirs, K.A., 2016. Catchment- and reach-scale controls on the distribution and expectation of geomorphic channel adjustment. Water Resources Research 52(5), 3408–3427.

Longfield, S.A., Macklin, M.G., 1999. The influence of recent environmental change on flooding and sediment fluxes in the Yorkshire Ouse basin. Hydrological processes 13, 1051–1066.

Macdonald, N., 2006. An underutilized resource: historical flood chronologies, a valuable resource in determining periods of hydro-geomorphic change. IAHS Publication 306, 120.

Macdonald, N., Phillips, I.D., Mayle, G., 2010. Spatial and temporal variability of flood seasonality in Wales. Hydrological Processes 24, 1806–1820.

Macdonald, N., Sangster, H., 2017. High-magnitude flooding across Britain since AD 1750. Hydrol Earth Syst Sc, 21(3), 1631-1650.

Mackereth, F.J.H., 1971. On the variation in direction of the horizontal component of remnant magnetisation in lake sediments. Earth and Planetary Science Letters 12, 332–338.

Macklin, M.G., 1986. Channel and floodplain metamorphosis in the River Nent, Cumberland. Quaternary River Landforms and Sediments in the Northern Pennines, England. Field Guide 19, 33.

Macklin, M.G., 1997. Fluvial Geomorphology of north-east England, in: Gregory, K.J. (Ed.), Fluvial Geomorphology of Great Britain. Chapman and Hall, London, 235–238.

Macklin, M.G., 1999. Holocene river environments in prehistoric Britain: human interaction and impact. Journal of Quaternary Science 14, 521–530.

Macklin, M.G., Jones, A.F., Lewin, J., 2010. River response to rapid Holocene environmental change: evidence and explanation in British catchments. Quaternary Science Reviews 29, 1555–1576.

Macklin, M.G., Lewin, J., 1989. Sediment transfer and transformation of an alluvial valley floor: the River South Tyne, Northumbria, UK. Earth Surface Processes and Landforms, 14(3), 233-246.

Macklin, M.G., Lewin, J., 1998. Channel, Floodplain and Drainage Basin Response to Environmental Change. In: Thorne C.R., Hey R.D., Newson M.D. (Eds.), Applied fluvial geomorphology for river engineering and management. John Wiley & Sons, Chichester, UK, 54-69.

Macklin, M.G., Lewin, J., 2008. Alluvial responses to the changing Earth system. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group 33, 1374–1395.

Macklin, M.G., Lewin, J., Jones, A.F., 2014. Anthropogenic alluvium: an evidence-based meta-analysis for the UK Holocene. Anthropocene 6, 26–38.

Macklin, M.G., Passmore, D., Newson, M., 1998. Controls of short and long term river instability: processes and patterns in gravel-bed rivers, the Tyne basin, northern England. Water Resources Publications: LLC Colorado, 257-278.

Macklin, M.G., Passmore, D.G., Newson, M.D., 1998. Controls of short and long term river instability: processes and patterns in gravel-bed rivers, the Tyne basin, northern England. Gravel Bed Rivers in the Environment, 257-278.

Macklin, M.G., Rumsby, B.T., Heap, T., 1992. Flood alluviation and entrenchment: Holocene valley-floor development and transformation in the British uplands. Geological Society of America Bulletin, 104(6), 631-643.

Magilligan, F.J., 1985. Historical floodplain sedimentation in the Galena River basin, Wisconsin and Illinois. Annals of the Association of American Geographers, 75(4), 583-594.

Magilligan, F.J., 1992. Thresholds and the spatial variability of flood power during extreme floods. Geomorphology, 5(3-5), 373-390.

Manley, G., 1946. The centenary of rainfall observations at Seathwaite. Weather 1, 163–168.

Marchi, L., Cavalli, M., Amponsah, W., Borga, M., Crema, S., 2016. Upper limits of flash flood stream power in Europe. Geomorphology 272, 68–77.

Marcus, W.A., Fonstad, M.A., 2010. Remote sensing of rivers: the emergence of a subdiscipline in the river sciences. Earth Surface Processes and Landforms, 35(15), 1867-1872.

Marr, J.E., 1916. The geology of the Lake District. Cambridge University Press.

Marshall, M.R., Ballard, C.E., Frogbrook, Z.L., Solloway, I., McIntyre, N., Reynolds, B., Wheater, H.S., 2013. The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots in upland UK. Hydrological Processes 28, 2617–2629.

Martin, Y., Church, M., 1995. Bed-material transport estimated from channel surveys: Vedder River, British Columbia. Earth Surface Processes and Landforms 20, 347-361.

Martínez-Fernández, V., del Tánago, M.G., de Jalón, D.G., 2019. Selecting geomorphic variables for automatic river segmentation: Trade-offs between information gained and effort required. Geomorphology, 329, 248-258.

Mayes, J., 1996. Spatial and temporal fluctuations of monthly rainfall in the British Isles and variations in the mid-latitude westerly circulation. International Journal of Climatology: A Journal of the Royal Meteorological Society 16, 585–596.

McCarthy, M., Spillane, S., Walsh, S., Kendon, M., 2016. The meteorology of the exceptional winter of 2015/2016 across the UK and Ireland. Weather, 71(12), 305-313.

McDougall, D., Evans, D., 2015. The Quaternary of the Lake District Field Guide. Quaternary Research Association. Nottinghamshire, 11-9.

McEwen, L.J., 1989. River channel changes in response to flooding in the upper River Dee catchment, Aberdeenshire, over the last 200 years. Floods: Hydrological, Sedimentological and Geomorphological Implications. John Wiley & Sons, New York. 219-238.

McEwen, L.J., 1994. Channel planform adjustment and stream power variations on the middle River Coe, Western Grampian Highlands, Scotland. Catena 21, 357–374.

McEwen, L.J., Werritty, A., 1988. The hydrology and long-term geomorphic significance of a flash flood in the Cairngorm Mountains, Scotland. Catena 15, 361–377.

McLean, D.G., Church, M., Tassone, B., 1999. Sediment transport along lower Fraser River - 1. Measurements and hydraulic computations. Water Resources Research, 35(8), 2533-2548.

Met Office., 2016. Flooding in Cumbria December 2015.https://www.metoffice.gov.uk/climate/uk/interesting/december2015. Last Accessed: February 2018

Met Office., 2017. Rainfall Amount annual average 1981 – 2010. https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/rain/how-much-does-it-rain-in-the-uk

Milan, D., Schwendel, A., 2019. Long-term channel response to a major flood in an upland gravel-bed river, in: Proceedings of the 38th IAHR World Congress September.

Milan, D.J., 2012. Geomorphic impact and system recovery following an extreme flood in an upland stream: Thinhope Burn, northern England, UK. Geomorphology, 138(1), 319-328.

Milan, D.J., Heritage, G.L. and Hetherington, D., 2007. Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel change in a proglacial river. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 32(11), 1657-1674.

Mill, H.R., 1895. Bathymetrical survey of the English Lakes. The Geographical Journal 6, 46–73.

Millar, R.G., 2000. Influence of bank vegetation on alluvial channel patterns. Water Resources Research 36, 1109–1118.

Millar, R.G., Quick, M.C., 1993. Effect of bank stability on geometry of gravel rivers. Journal of Hydraulic Engineering 119, 1343–1363.

Miller, H., Croudace, I.W., Bull, J.M., Cotterill, C.J., Dix, J.K., Taylor, R.N., 2014. A 500 year sediment lake record of anthropogenic and natural inputs to Windermere (English Lake District) using double-spike lead isotopes, radiochronology, and sediment microanalysis. Environmental science & technology 48, 7254–7263.

Miller, S.N., Guertin, D.P. and Goodrich, D.C., 2002. Deriving stream channel morphology using GIS-based watershed analysis. In GIS for Water Resource and Watershed Management, 71-78. CRC Press. London.

Miller, S.N., Guertin, D.P., Goodrich, D.C., 2003. Deriving stream channel morphology using GIS-based watershed analysis. GIS for water resources and watershed management, 71-78. CRC Press.

Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic Tectonic Control of Sediment Discharge to the Ocean - the Importance of Small Mountainous Rivers. Journal of Geology, 100(5), 525–544.

Millward, D., Marriner, G.F., Beddoe-Stephens, B., 2000. The eycott volcanic group, an ordovician continental margin andesite suite in the English Lake District. Proceedings of the Yorkshire Geological Society 53, 81–96.

Milne, J., 1983a. Patterns of confinement in some stream channels of upland Britain. Geografiska Annaler. Series A. Physical Geography, 65(1/2), 67-83.

Milne, J.A., 1982. River Channel Change in the Harthorpe Valley, Northumberland, since 1897. University of Newcastle Upon Tyne, no. 13.

Milne, J.A., 1983b. Variation in Cross-Sectional Asymmetry of Coarse Bedload River Channels. Earth Surface Processes and Landforms 8, 503–511.

Milton, E.J., Gilvear, D.J., Hooper, I.D., 1995. Investigating change in fluvial systems using remotely sensed data, in: Gurnell, A.M., Petts, G.E. (Eds.), Changing River Channels. John Wiley & Sons, Chichester, 276–301.

Moir, D.G. and Inglis, H.R., 1973. The early maps of Scotland to 1850 (Vol. 1). Royal Scottish Geographical Society. Scotland.

Monkhouse, F.J., 1960. The English Lake District, in: Edwards, K.C. (Ed.), British Landscapes Through Maps I. The Geographical Association, Sheffield.

Montgomery, D.R., 1999. Process domains and the river continuum 1. JAWRA Journal of the American Water Resources Association, 35(2), 397-410.

Montgomery, D.R., Buffington, J.M., 1993. Channel classification, prediction of channel response, and assessment of channel condition. Department of Geological Sciences and Quaternary Research Centre, University of Washington, Washington.

Moore, R.J., Newson, M.D., 1986. Production, Storage and Output of Coarse Upland Sediments - Natural and Artificial Influences as Revealed by Research Catchment Studies. J Geol Soc London, 143, 921-926.

Moseley, F., 1978. The geology of the Lake District. Yorkshire Geological Society.

Nagel, D.E., Buffington, J.M., Parkes, S.L., Wenger, S., Goode, J.R., 2014. A landscape scale valley confinement algorithm: delineating unconfined valley bottoms for geomorphic, aquatic, and riparian applications.

Nanson, G.C. and Knighton, A.D., 1996. Anabranching rivers: their cause, character and classification. Earth surface processes and landforms, 21(3), 217-239.

Nanson, G.C., 1986. Episodes of vertical accretion and catastrophic stripping: a model of disequilibrium flood-plain development. Geological Society of America Bulletin, 97(12), 1467-1475.

National Trust., 2019. Restoring Ullswater's Rivers: National Trust Ullswater Rivers Scheme. https://nt.global.ssl.fastly.net/aira-force-and-ullswater/documents/ullswater-rivers-scheme-faqs.pdf

Neill, C.R., 1987. Sediment balance considerations linking long-term transport and channel processes. Sediment Transport in Gravel-Bed Rivers. John Wiley and Sons New York, 225-249.

Newson, M., 1980a. The geomorphological effectiveness of floods—a contribution stimulated by two recent events in mid-Wales. Earth Surface Processes, 5(1), 1-16.

Newson, M., 1980b. The erosion of drainage ditches and its effect on bed-load yields in mid-Wales: reconnaissance case studies. Earth Surface Processes 5, 275–290.

Newson, M., 1989. Flood effectiveness in river basins: progress in Britain in a decade of drought. K. Beven, P. Carling (Eds.), Floods: Hydrological, Sedimentological and Geomorphological Implications, Wiley, Chichester (1989), pp. 151-169

Newson, M., 1997. Time, scale and change in river landscapes: the jerky conveyor belt. Landscape Research, 22(1), 13-23.

Newson, M.D., 1981. Mountain streams, in: Lewin, J. (Ed.), British Rivers. George Allen & Unwin, London, 59–89.

Newton, M., 1971. The sand and gravel industry in N.E England, in: Department of Geography Research Series. University of Newcastle-upon-Tyne, Newcastle-upon-Tyne, pp. 78.

Nicholas, A., Ashworth, P., Kirkby, M., Macklin, M., Murray, T., 1995. Sediment slugs: large-scale fluctuations in fluvial sediment transport rates and storage volumes. Prog Phys Geog, 19(4), 500-519.

Nunnally, N.R., Keller, E., 1979. Use of fluvial processes to minimize adverse effects of stream channelization. No. 144, Water Resources Research Institute of the University of North Carolina.

O'Brien, G.R., Wheaton, J.M., Fryirs, K., Macfarlane, W.W., Brierley, G., Whitehead, K., Gilbert, J., Volk, C., 2019. Mapping Valley Bottom Confinement at the Network Scale. Earth Surface Processes and Landforms. 44(9), 1828-1845.

Odgaard, A.J., 1987. Streambank erosion along two rivers in Iowa. Water Resour Res, 23(7), 1225-1236.

Orr, H.G., Block, C., Newson, M.D., 2000. Kent Catchment Geomorphological Appraisal. HYSED Report to Environment Agency; North-West Region, University of Lancaster: Lancaster, UK.

Orr, H.G., Carling, P.A., 2006. Hydro-climatic and land use changes in the River Lune catchment, North West England, implications for catchment management. River Research and Applications 22, 239–255.

Otto, J.C., Schrott, L., Jaboyedoff, M., Dikau, R., 2009. Quantifying sediment storage in a high alpine valley (Turtmanntal, Switzerland). Earth Surface Processes and Landforms, 34(13), 1726-1742.

Owens, P.N., Walling, D.E., 2002. Changes in sediment sources and floodplain deposition rates in the catchment of the River Tweed, Scotland, over the last 100 years: the impact of climate and land use change. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group 27, 403–423.

Oyedotun, T.D.T., 2011. Long-term change of the River Liza, Wild Ennerdale, England. River Basin Management, VI, WIT Press, Southampton, UK, 251-262.

Page, K.J., Heerdegen, F.G., 1985. Channel change on the lower Manawatu River. New Zealand Geographer 41, 35–38.

Parsons, H., Gilvear, D., 2002. Valley floor landscape change following almost 100 years of flood embankment abandonment on a wandering gravel-bed river. River Research and Applications 18, 461–479.

Passmore, D.G., Macklin, M.G., Brewer, P.A., Lewin, J., Rumsby, B.T. and Newson, M.D., 1993. Variability of late Holocene braiding in Britain. Geological Society, London, Special Publications, 75(1), 205-229.

Pattison, I., Lane, S.N., 2012. The relationship between Lamb weather types and long-term changes in flood frequency, River Eden, UK. International Journal of Climatology, 32(13), 1971-1989.

Pennington, W., 1964. Pollen analyses from the deposits of six upland tarns in the Lake District. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 248, 205–244.

Pennington, W., 1965. The interpretation of some post-glacial vegetation diversities at different Lake District sites. Proceedings of the Royal Society of London. Series B. Biological Sciences 161, 310–323.

Pennington, W., 1981. Records of a lake's life in time: the sediments. Hydrobiologia 79, 197–215.

Pennington, W., 1991. Palaeolimnology in the English Lakes—some questions and answers over fifty years, in: Environmental History and Palaeolimnology. Springer, 9–24.

Petit, F., Gob, F., Houbrechts, G., Assani, A., 2005. Critical specific stream power in gravel-bed rivers. Geomorphology, 69(1-4), 92-101.

Petterson, M.G., Beddoe-Stephens, B., Millward, D., Johnson, E.W., 1992. A pre-caldera plateau-andesite field in the Borrowdale Volcanic Group of the English Lake District. Journal of the Geological Society 149, 889–906.

Petts, G.E. 1979. Complex response of river channel morphology subsequent to reservoir construction, Progress in Physical Geography, 3(3), 329-362.

Petts, G.E., 1980. Implications of the fluvial process—channel morphology interaction below British reservoirs for stream habitats. Science of the Total Environment 16, 149–163.

Petts, G.E., Gurnell, A.M., 2005. Dams and geomorphology: research progress and future directions. Geomorphology, 71(1), 27-47.

Petts, G.E., Lewin, J., 1979. Physical effects of reservoirs on river systems. Geo Abstracts.

Petts, G.E., Möller, H., Roux, A.L., 1989. Historical change of large alluvial rivers: Western Europe. John Wiley & Sons, Chichester.

Petts, G.E., Thoms, M.C., 1986. Channel aggradation below Chew valley lake, Somerset, UK. Catena, 13(3), 305-320.

Phillips, J.D., 1991. Fluvial Sediment Budgets in the North-Carolina Piedmont. Geomorphology, 4(3-4), 231-241.

Phillips, J.D., 2007. The perfect landscape. Geomorphology 84, 159–169.

Picco, L., Bertoldi, W., Comiti, F., 2017. Dynamics and ecology of wood in world rivers, Geomorphology, 279, 1–2.

Pickup, G., Warner, R.F., 1976. Effects of hydrologic regime on magnitude and frequency of dominant discharge. Journal of Hydrology 29, 51–75.

Piégay, H., Arnaud, F., Belletti, B., Bertrand, M., Bizzi, S., Carbonneau, P., Dufour, S., Liébault, F., Ruiz-Villanueva, V., Slater, L., 2020. Remotely sensed rivers in the Anthropocene: state of the art and prospects. Earth Surface Processes and Landforms 45, 157–188.

Piégay, H., Chabot, A., Le Lay, Y.F. 2018. Some comments about resilience: From cyclicity to trajectory, a shift in living and nonliving system theory, Geomorphology, 106527.

Piégay, H., Gurnell, A.M., 1997. Large woody debris and river geomorphological pattern: examples from S.E. France and S. England. Geomorphology 19, 99–116.

Piégay, H., Mathias Kondolf, G., Sear, D.A., 2016. Integrating geomorphological tools to address practical problems in river management and restoration. In: Kondolf, M.G., Piégay, H., (Eds) Tools in fluvial geomorphology, 22, 507–532.

Pique, G., Batalla, R.J., Lopez, R., Sabater, S., 2017. The fluvial sediment budget of a dammed river (upper Muga, southern Pyrenees). Geomorphology 293, 211–226.

Pitlick, J., Cui, Y., Wilcock, P., 2009. Manual for computing bed load transport using BAGS (Bedload Assessment for Gravel-bed Streams) Software.

Playfair, J., 1802. Illustrations of the Huttonian Theory of the Earth. Dover, London.

Polvi, L.E. and Wohl, E., 2013. Biotic drivers of stream planform: implications for understanding the past and restoring the future. BioScience, 63(6), 439-452.

Prosser, I.P., Hughes, A.O., Rutherfurd, I.D., 2000. Bank erosion of an incised upland channel by subaerial processes: Tasmania, Australia. Earth Surface Processes and Landforms, 25(10), 1085-1101.

Rapp, A., 1960. Recent development of mountain slopes in Kärkevagge and surroundings, northern Scandinavia. Geografiska Annaler 42, 65–200.

Raven, E.K., Lane, S.N., Bracken, L.J., 2010. Understanding sediment transfer and morphological change for managing upland gravel-bed rivers. Progress in Physical Geography 34, 23–45.

Raven, E.K., Lane, S.N., Ferguson, R.I., Bracken, L.J., 2009. The spatial and temporal patterns of aggradation in a temperate, upland, gravel-bed river. Earth Surface Processes and Landforms 34, 1181–1197.

Raven, P.J., Fox, P., Everard, M., Holmes, N.T.H., and Dawson, F.H., 1997. River Habitat Survey: a new system for classifying rivers according to their habitat quality. Freshwater quality: Defining the indefinable, 215-234.

Reid, H., 2014. Thirlmere Gravel Management. Environment Agency, Cumbria, pp. 23.

Reid, H.E., Williams, R.D., Brierley, G.J., Coleman, S.E., Lamb, R., Rennie, C.D. and Tancock, M.J., 2019. Geomorphological effectiveness of floods to rework gravel bars: insight from hyperscale topography and hydraulic modelling. Earth Surface Processes and Landforms, 44(2), pp.595-613.

Reid, I., Frostick, L.E., Layman, J.T., 1985. The incidence and nature of bedload transport during flood flows in coarse-grained alluvial channels. Earth Surface Processes and Landforms 10, 33–44.

Reid, L.M., Dunne, T., 1996. Rapid evaluation of sediment budgets. Catena Reiskirchen, Germany.

Reid, L.M., Dunne, T., 2003. Sediment budgets as an organizing framework in fluvial geomorphology. Tools in fluvial geomorphology, 357-380.

Reinfelds, I., Cohen, T., Batten, P., Brierley, G., 2004. Assessment of downstream trends in channel gradient, total and specific stream power: a GIS approach. Geomorphology, 60(3-4), 403-416.

RESTORE., 2019. Case study: Swindale Beck Restoration. https://restorerivers.eu/wiki/index.php?title=Case_study%3ASwindale_Beck_Restoration

Rice, S.P., Church, M., Wooldridge, C.L. and Hickin, E.J., 2009. Morphology and evolution of bars in a wandering gravel-bed river; lower Fraser river, British Columbia, Canada. Sedimentology, 56(3), 709-736.

Richards, K.S., 1982. Rivers: form and process in alluvial channels. London: Methuen.

Richardson, M.J., 2011. Newlands Beck at Portinscale photograph: https://www.geograph.org.uk/photo/2368488

Righini, M., Surian, N., Wohl, E., Marchi, L., Comiti, F., Amponsah, W., Borga, M., 2017. Geomorphic response to an extreme flood in two Mediterranean rivers (northeastern Sardinia, Italy): Analysis of controlling factors. Geomorphology, 290, 184-199.

Rinaldi, M., Gurnell, A., Del Tánago, M.G., Bussettini, M., Hendriks, D., 2016. Classification of river morphology and hydrology to support management and restoration. Aquatic sciences, 78(1), 17-33.

Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: The Morphological Quality Index (MQI). Geomorphology, 180, 96-108.

Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2015a. A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology, 251, 122-136.

Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., Nardi, L., Lastoria, B., 2015b. IDRAIM: A Methodological Framework for Hydromorphological Analysis and Integrated River Management of Italian Streams. Engineering Geology for Society and Territory, Vol 3: River Basins, Reservoir Sedimentation and Water Resources, 301-304.

Roberts, N.M., Cole, S.J., Forbes, R.M., Moore, R.J., Boswell, D., 2009. Use of high-resolution NWP rainfall and river flow forecasts for advance warning of the Carlisle flood, north-west England. Meteorological Applications, 16(1), 23-34.

Robson, A., Reed, D., 1999. Flood Estimation Handbook. Statistical Procedures for flood frequency estimation, 3. Institute of Hydrology, Oxfordshire.

Rodger, E.M., 1972. The large-scale county maps of the British Isles, 1956 - 1980: A Union List. Bodleian Library, Oxford.

Rodwell, M. J. & Folland, C. K., 2002. Atlantic air–sea interaction and seasonal predictability. Quart. J. Roy. Met. Soc. 128, 1413–1443.

Rodwell, M. J., Rowell, D. P. & Folland, C. K., 1999. Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. Nature 398, 320–323.

Rosgen, D.L., 1994. A classification of natural rivers. Catena, 22(3), 169-199.

Rowland, C.S., Morton, R.D., Carrasco, L., McShane, G., O'Neil, A.W., Wood, C.M., (2017) Land Cover Map 2015 (vector, GB). NERC Environmental Information Data Centre: https://doi.org/10.5285/6c6c9203-7333-4d96-88ab-78925e7a4e73

RRC, 2013. Manual of River Restoration Techniques, 3rd ed. River Restoration Centre, Bedford.

RRC., 2018. River Restoration Centre's National River Restoration Inventory (NRRI): www.therrc.co.uk/national-river-restoration-inventory-nrri

Rumsby, B. T., Macklin, M.G., 1994. Channel and floodplain response to recent abrupt climate change: the Tyne basin, northern England. Earth Surface Processes and Landforms, 19(6), 499-515.

Rumsby, B.T., 2001. Valley-floor and floodplain processes. Geomorphological processes and landscape change: Britain in the last 1000 years, 90–115.

Rumsby, B.T., Macklin, M.G., 1996. River response to the last neoglacial (the 'Little Ice Age') in northern, western and central Europe. Geological Society, London, Special Publications 115, 217–233.

Sansom, A.L., 1999. Upland vegetation management: the impacts of overstocking. Water Science and Technology 39, 85.

Schillereff, D.N., Chiverrell, R.C., Macdonald, N., Hooke, J.M., Welsh, K.E., 2016. Quantifying system disturbance and recovery from historical mining-derived metal contamination at Brotherswater, northwest England. Journal of Paleolimnology 56, 205–221.

Schmitt, R.J., Bizzi, S. and Castelletti, A., 2016. Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity. Water Resources Research, 52(5), 3941-3965.

Schumm, S.A., 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geological society of America bulletin 67, 597–646.

Schumm, S.A., 1969. River metamorphosis. Journal of the Hydraulics division 95, 255–274.

Schumm, S.A., 1977. The Fluvial System. John Wiley and Sons, New York.

Schumm, S.A., 1985. Patterns of alluvial rivers. Annual Review of Earth and Planetary Sciences, 13(1), 5-27.

Schumm, S.A., 2005. River variability and complexity. Cambridge University Press.

Schumm, S.A., Lichty, R.W., 1965. Time, space, and causality in geomorphology. American Journal of Science, 263(2), 110-119.

Sear, D.A., 1994. River restoration and geomorphology. Aquatic Conservation: Marine and Freshwater Ecosystems 4, 169–177.

Sear, D.A., Archer, D.R., 1998. The effects of gravel extraction on the stability of gravel-bed rivers: A case study from the Wooler Water, Northumberland, UK. Gravel bed rivers in the environment, edited by: Klingeman, P., Beschta, RL, Komar, BD, and Milhous, RT, Water Res. Council, Colorado, USA 415, 432.

Sear, D.A., Millington, C.E., Kitts, D.R. and Jeffries, R., 2010. Logjam controls on channel: floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. Geomorphology, 116(3-4). 305-319.

Sear, D.A., Newson, M,D., Brookes, A., 1995. Sediment related river maintenance: the role of fluvial geomorphology. Earth Surface Processes and Landforms 20, 629–647.

Sear, D.A., Newson, M.D., 2003. Environmental change in river channels: a neglected element. Towards geomorphological typologies, standards and monitoring. Sci Total Environ, 310(1-3), 17-23.

Sear, D.A., Newson, M.D., Thorne, C.R., 2003. Guidebook of applied fluvial geomorphology. 0727741012, DEFRA, London.

Sear, D.A., Wilcock, D., Robinson, M.R., Fisher, K.R., 2000. Channel modifications and impacts. The changing hydrology of the UK. Routledge, London 55–81.

Sear, D.W., J. Neal, J. Andersen, E. Leyalnd, J. Hornby, D. Bates, P. Murdoch, A. Dearing, J, 2017. Valley and human controls on the geomorphic responses to an extreme flood, Cumbrian Floods Partnership Geomorphology Workshop Penrith, UK.

Selby, M.J., 1985. Earth's changing surface: an introduction to geomorphology. Oxford University Press, New York.

Shields, F.D., Simon, A., Steffen, L.J., 2000. Reservoir effects on downstream river channel migration. Environmental Conservation 27, 54–66.

Sibley, A., 2010. Analysis of extreme rainfall and flooding in Cumbria 18–20 November 2009. Weather, 65(11), 287-292.

Simon, A., Castro, J. and Rinaldi, M., 2016. Channel form and adjustment: characterization, measurement, interpretation and analysis. Tools in Fluvial Geomorphology, 235-259.

Sissons, J.B., 1980. The Loch Lomond Advance in the Lake District, northern England. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 71, 13–27.

Skelton, R.A., 1970. County Atlases of the British Isles, 1579-1850. Carta Press. London.

Skinner, K.S. and Haycock, N.E, 2004, Wasdale – Fluvial Audit of the Lingmell Beck and Mosedale Beck systems, prepared for the National Trust, Haycock Associates Limited, Pershore.

Slaymaker, O., 1991. Mountain geomorphology: a theoretical framework for measurement programmes. Catena, 18(5), 427-437.

Slaymaker, O., 2003. The sediment budget as conceptual framework and management tool, The Interactions Between Sediments and Water. Springer, 71-82.

Slingerland, R., Smith, N.D., 2004. River avulsions and their deposits. Annu. Rev. Earth Planet. Sci., 32, 257-285.

Sloan, J., Miller, J.R., Lancaster, N., 2001. Response and recovery of the Eel River, California, and its tributaries to floods in 1955, 1964, and 1997. Geomorphology, 36(3), 129-154.

Smith, A., 2019. Lakeland Rocks. The Crowood Press Ltd., Wiltshire.

Smith, B., 1910. Some recent changes in the course of the Trent. Geographical Journal XXXV, 568–579.

Smith, H.G. and Dragovich, D., 2008. Sediment budget analysis of slope–channel coupling and in-channel sediment storage in an upland catchment, southeastern Australia. Geomorphology, 101(4), 643-654.

Snyder, N.P. and Kammer, L.L., 2008. Dynamic adjustments in channel width in response to a forced diversion: Gower Gulch, Death Valley National Park, California. Geology, 36(2), 187-190.

Soar, P.J., Wallerstein, N.P., Thorne, C.R., 2017. Quantifying River Channel Stability at the Basin Scale. Water 9(2), 133, 1-31.

South Cumbria Rivers Trust., 2019. River Restoration: https://scrt.co.uk/what-we-do/habitat-improvement/river-restoration/

Stephenson, D., Bevins, R.E., Millward, D., Stone, P., Wadsworth, W.J., 1999. Caleodnian Igneous Rocks of Great Britain, in: Geological Conservation Review. Peterborough.

Stewart, L., Morris, D., Jones, D., Spencer, P., 2010. Extreme rainfall in Cumbria, November 2009-an assessment of storm rarity, BHS Third International Symposium, Managing Consequences of a Changing Global Environment, Newcastle.

Stewart, L., Vesuviano, G., Morris, D. and Prosdocimi, I., 2014. The new FEH rainfall depth-duration-frequency model: results, comparisons and implications. 12th British Hydrological Society National Symposium, Birmingham, UK, 2–4 Sept.

Stone, P., Cooper, A.H., Evans, J.A., 1999. The Skiddaw Group (English Lake District) reviewed: early Palaeozoic sedimentation and tectonism at the northern margin of Avalonia. Geological Society, London, Special Publications 160, 325–336.

Stone, P., Millward, D., Young, B., Merritt, J.W., Clarke, S.M., McCormac, M., Lawrence, D.J.D., 2010. British Regional Geology: Northern England, 5th ed. British Geological Survey, Nottingham.

Stott, T., 1997. A comparison of stream bank erosion processes on forested and moorland streams in the Balquhidder catchments, central Scotland. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Group 22, 383–399.

Stouthamer, E., Berendsen, H.J., 2001. Avulsion frequency, avulsion duration, and interavulsion period of Holocene channel belts in the Rhine-Meuse delta, the Netherlands. Journal of Sedimentary Research, 71(4), 589-598.

Strahler, A. N. 1952. Dynamic basis of geomorphology. Geological Society of America Bulletin, 63, 923-938.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union, 38(6), 913-920.

Surian, N. and Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology, 50(4), 307-326.

Surian, N., Righini, M., Lucía, A., Nardi, L., Amponsah, W., Benvenuti, M., Borga, M., Cavalli, M., Comiti, F., Marchi, L., 2016. Channel response to extreme floods: insights on controlling factors from six mountain rivers in northern Apennines, Italy. Geomorphology 272, 78–91.

Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50, 307–326.

Tangi, M., Schmitt, R., Bizzi, S. and Castelletti, A., 2019. The CASCADE toolbox for analyzing river sediment connectivity and management. Environmental Modelling & Software, 119, 400-406.

Tanguy, M., Dixon, H., Prosdocimi, I., Morris, D.G., Keller, V.D.J., 2019. Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890-2017) [CEH-GEAR]. https://doi.org/10.5285/ee9ab43d-a4fe-4e73-afd5-cd4fc4c82556

Tate, W.E., 1978. A Domesday of English enclosure acts and awards. University of Reading, Reading.

Taylor, B.J., Burgess, I.C., Land, D.H., Mills, D.A.C., Smith, D.B., Warren, M.A., 1971. Northern England, in: British Regional Geology. Natural Environment Research Council, Institute of Geological Sciences, HMSO, London.

Taylor, J., 1864. Description of the River Tees and of the works upon it connected with navigation. Minutes and Proceedings of the Institute of Civil Engineers XXIV, 62–103.

Taylor, M.P., Macklin, M.G., 1997. Holocene alluvial sedimentation and valley floor development: the River Swale, Catterick, North Yorkshire, UK. Proceedings of the Yorkshire Geological Society 51, 317–327.

Thomas, M.F., 2001. Landscape sensitivity in time and space—an introduction. Catena, 42(2-4), 83-98.

Thompson, C., Croke, J., 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer valley, southeast Queensland, Australia. Geomorphology, 197, 156-169.

Thompson, C.J., Fryirs, K., Croke, J., 2016. The Disconnected Sediment Conveyor Belt: Patterns of Longitudinal and Lateral Erosion and Deposition during a Catastrophic Flood in the Lockyer Valley, South East Queensland, Australia. River Res Appl, 32(4), 540-551.

Thoms, M. C., Gilvear, D. J., Greenwoood, M. T., & Wood, P. J. (2016). An introduction to river science: Research and applications. In: River science: Research and management for the 21st century Chichester: Wiley Blackwell, 1–14.

Thorne, C.R., 1997. Channel types and morphological classification. In: Thorne C.R., Hey R.D., Newson M.D. (Eds.), Applied fluvial geomorphology for river engineering and management. John Wiley & Sons, Chichester, UK, 175-222.

Thorne, C.R., 1998. Stream reconnaissance handbook: geomorphological investigation and analysis of river channels. John Wiley & Sons Ltd., Chichester.

Thorne, C.R., Amarasinghe, I., Gardiner, J., Perala-Gardiner Sellin, R., 1997. Bank protection using vegetation with special reference to willows. Engineering and Physical Sciences Research Council and Environmental Agency Report.

Trimble, S.W., 1983. A Sediment Budget for Coon Creek Basin in the Driftless Area, Wisconsin, 1853-1977. American Journal of Science, 283(5), 454-474.

Trimble, S.W., 2010. Streams, valleys and floodplains in the sediment cascade. Sediment Cascades: An Integrated Approach, 307-343.

Trimble, S.W., Mendel, A.C., 1995. The cow as a geomorphic agent—a critical review. Geomorphology 13, 233–253.

Trimming, P., 2015. River Greta near Keswick photograph: https://www.geograph.org.uk/photo/4567177

Tufnell, L., 1997. North-West England and the Isle of Man, in: Wheeler, D., Mays, J. (Eds.), Regional Climates of the British Isles. Routledge, London, pp. 150–189.

Turner, G.M., Thompson, R., 1981. Lake sediment record of the geomagnetic secular variation in Britain during Holocene times. Geophysical Journal International 65, 703–725.

van Oldenborgh, G.J., Otto, F.E., Haustein, K. and Cullen, H., 2015. Climate change increases the probability of heavy rains like those of storm Desmond in the UK–an event attribution study in near-real time. Hydrology and Earth System Sciences Discussions, 12(12), 13197-13216.

Vargas-Luna, A., Duró, G., Crosato, A., Uijttewaal, W., 2019. Morphological adaptation of river channels to vegetation establishment: a laboratory study. Journal of Geophysical Research: Earth Surface 124, 1981–1995.

Vaughan, R., 1610. Water Workes. George Eld, London.

Verstraeten, G., Prosser, I.P., 2008. Modelling the impact of land-use change and farm dam construction on hillslope sediment delivery to rivers at the regional scale. Geomorphology 98, 199–212.

Wallace, M., Atkins, J., 1997. A medium term study of the Salmonid populations in St John's Beck and the River Glenderamackin (River Derwent, Cumbria) 1974 to 1996. Environment Agency, Cumbria.

Wallerstein, N, P., Soar, P, J. Thorne, C.R., 2006. River Energy Auditing Scheme (REAS) for catchment flood management planning. Proceedings of the IAHR River Flow, Lisbon, Portugal, 6-8.

Walling, D.E., 1983. The sediment delivery problem. Journal of hydrology, 65(1-3), 209-237.

Warburton, J., 2010. Sediment Transfer in Steep Upland Catchments (Northern England, UK): Landform and Sediment Source Coupling, in: Otto, J.-C., Dikau, R. (Eds.), Landform - Structure, Evolution, Process Control. Springer Berlin Heidelberg, 165–183.

Warburton, J., Danks, M., Wishart, D., 2002. Stability of an upland gravel-bed stream, Swinhope Burn, Northern England. Catena, 49(4), 309-329.

Warburton, J., Kincey, M., Johnson, R.M., 2016. Assessment of Torrent Erosion Impacts on the Eastern Flank of Thirlmere Reservoir and A591 (Cumbria) following Storm Desmond 2015, Durham University, Durham.

Warburton, J., Milledge, D.G., Johnson, R.M., 2008. Assessment of shallow landslide activity following the January 2005 storm, Northern Cumbria. Proceedings of the Cumberland Geological Society 7:263-283.

Ward, J.C., 1873. The glaciation of the northern part of the Lake District. Quarterly Journal of the Geological Society 29, 422–441.

Ward, J.C., 1875. The glaciation of the southern part of the Lake District and the glacial origin of the lakes of Cumberland and Westmoreland. Quarterly Journal of the Geological Society 152–166.

Warren, S.D., Thurow, T.L., Blackburn, W.H., Garza, N.E., 1986. The influence of livestock trampling under intensive rotation grazing on soil hydrologic characteristics. Rangeland Ecology & Management/Journal of Range Management Archives 39, 491–495.

Wathen, S.J., Hoey, T.B., 1998. Morphological controls on the downstream passage of a sediment wave in a gravel-bed stream. Earth Surface Processes and Landforms 23, 715–730.

Watkins, S., Whyte, I., 2008. Extreme Flood Events in Upland Catchments in Cumbria since 1600: the evidence of historical records. North West Geography, 8(1), 33-41.

Watts, G., Battarbee, R.W., Bloomfield, J.P., Crossman, J., Daccache, A., Durance, I., Elliott, J.A., Garner, G., Hannaford, J., Hannah, D.M., 2015. Climate change and water in the UK–past changes and future prospects. Progress in Physical Geography 39, 6–28.

Werritty, A. and Leys, K.F., 2001. The sensitivity of Scottish rivers and upland valley floors to recent environmental change. Catena, 42(2-4), 251-273.

Werritty, A., Hoey, T., 2004. Trends and Issues: Geomorphological changes and trends in Scotland - trends in river channels and processes, Scottish Natural Heritage, Edingburgh.

Werritty, A., Leys, K.F., 2001. The sensitivity of Scottish rivers and upland valley floors to recent environmental change. Catena 42, 251–273.

Werrity, A., Ferguson, R.I., 1980. Pattern changes in a Scottish braided river over 1, 30 and 200 years, in: Cullingford, R.A., Davidson, D.A., Lewin, J. (Eds.), Timescale in Geomorphology. John Wiley & Sons, Great Britain, 53–68.

West Cumbria Rivers Trust., 2019. River Restoration Projects: https://westcumbriariverstrust.org/projects

Wheaton, J.M., Brasington, J., Darby, S.E. and Sear, D.A., 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth surface processes and landforms: the journal of the British Geomorphological Research Group, 35(2), 136-156.

Wheaton, J.M., Brasington, J., Darby, S.E., Kasprak, A., Sear, D. and Vericat, D., 2013. Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river. Journal of Geophysical Research: Earth Surface, 118(2), 759-779.

White, R.F., 1988. A Pennine gap? The Roman period in the North Yorkshire Dales. Recent Research in Roman Yorkshire. Studies in Honour of Mary Kitson Clark (Mrs Derwas Chitty), BAR British Series 193, 197–217.

Whiting, P.J., Bradley, J.B., 1993. A process-based classification system for headwater streams. Earth Surface Processes and Landforms 18, 603–612.

Wicherski, W., Dethier, D.P., Ouimet, W.B., 2017. Erosion and channel changes due to extreme flooding in the Fourmile Creek catchment, Colorado. Geomorphology.

Wilby, R.L., O'hare, G., Barnsley, N. 1, 1997. The North Atlantic Oscillation and British Isles climate variability, 1865–1996. Weather 52, 266–276.

Wilcock, P.R., Crowe, J.C., 2003. Surface-based transport model for mixed-size sediment. Journal of Hydraulic Engineering, 129(2), 120-128.

Williams, G., Costa, J., 1988. Geomorphic Measurements after a Flood. In: Baker V.R., Kochel R.C., Patton P.C. (Eds.), Flood Geomorphology. John Wiley and Sons, Canada, 65-80.

Williams, G.P., 1983. Paleohydrological methods and some examples from Swedish fluvial environments: I cobble and boulder deposits. Geografiska Annaler: Series A, Physical Geography, 65(3-4), 227-243.

Williams, G.P., Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers, Professional Paper 1286. US Geological Survey.

Williams, R.D., Bangen, S., Gillies, E., Kramer, N., Moir, H., Wheaton, J., 2020. Let the river erode! Enabling lateral migration increases geomorphic unit diversity. Science of the Total Environment 715, 136817.

Wilson, P., 2005. Paraglacial rock-slope failures in Wasdale, western Lake District, England: morphology, styles and significance. Proceedings of the Geologists' Association, 116(3-4), 349-361.

Wilson, P., 2010. Lake District Mountain Landforms. Scotforth Books.

Winterbottom, S.J., 2000. Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland. Geomorphology, 34(3), 195-208.

Winterbottom, S.J., Gilvear, D.J., 2000. A GIS-based approach to mapping probabilities of river bank erosion: regulated River Tummel, Scotland. River Research and Applications 16, 127–140.

Wishart, D., 2004. A combined catchment and reach-based assessment of historical channel planform change in a UK upland gravel-bed river. Durham theses, Durham University.

Wishart, D., Warburton, J., Bracken, L., 2008. Gravel extraction and planform change in a wandering gravel-bed river: The River Wear, Northern England. Geomorphology 94, 131–152.

Wishart, D., Warburton, J., Bracken, L., 2008. Gravel extraction and planform change in a wandering gravel-bed river: The River Wear, Northern England. Geomorphology, 94 (1-2), 131-152.

Wohl, E., 2015. Legacy effects on sediments in river corridors. Earth-Science Reviews 147, 30–53.

Wohl, E., 2019. Forgotten Legacies: Understanding and Mitigating Historical Human Alterations of River Corridors. Water Resources Research 55, 5181–5201.

Wohl, E., Angermeier, P.L., Bledsoe, B., Kondolf, G.M., MacDonnell, L., Merritt, D.M., Palmer, M.A., Poff, N.L., Tarboton, D., 2005. River restoration. Water Resources Research 41 W10301, 1-12.

Wohl, E., Lane, S.N., Wilcox, A.C., 2015. The science and practice of river restoration. Water Resources Research 51, 5974–5997.

Wolman, M.G., 1954. A method of sampling coarse river-bed material. EOS, Transactions American Geophysical Union, 35(6), 951-956.

Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes and Landforms, 3(2), 189-208.

Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. The Journal of Geology, 68(1), 54-74.

Wong, J.S., Freer, J.E., Bates, P.D., Sear, D.A., Stephens, E.M., 2015. Sensitivity of a hydraulic model to channel erosion uncertainty during extreme flooding. Hydrological processes 29, 261–279.

Wordsworth, W., 1835. Guide to the Lakes, 5th ed. Oxford University Press, Oxford.

Zar, J.H., 2010. Comparing Simple Linear Regression Equations, Biostatistical Analysis. Pearson Prentice Hall.