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

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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

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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

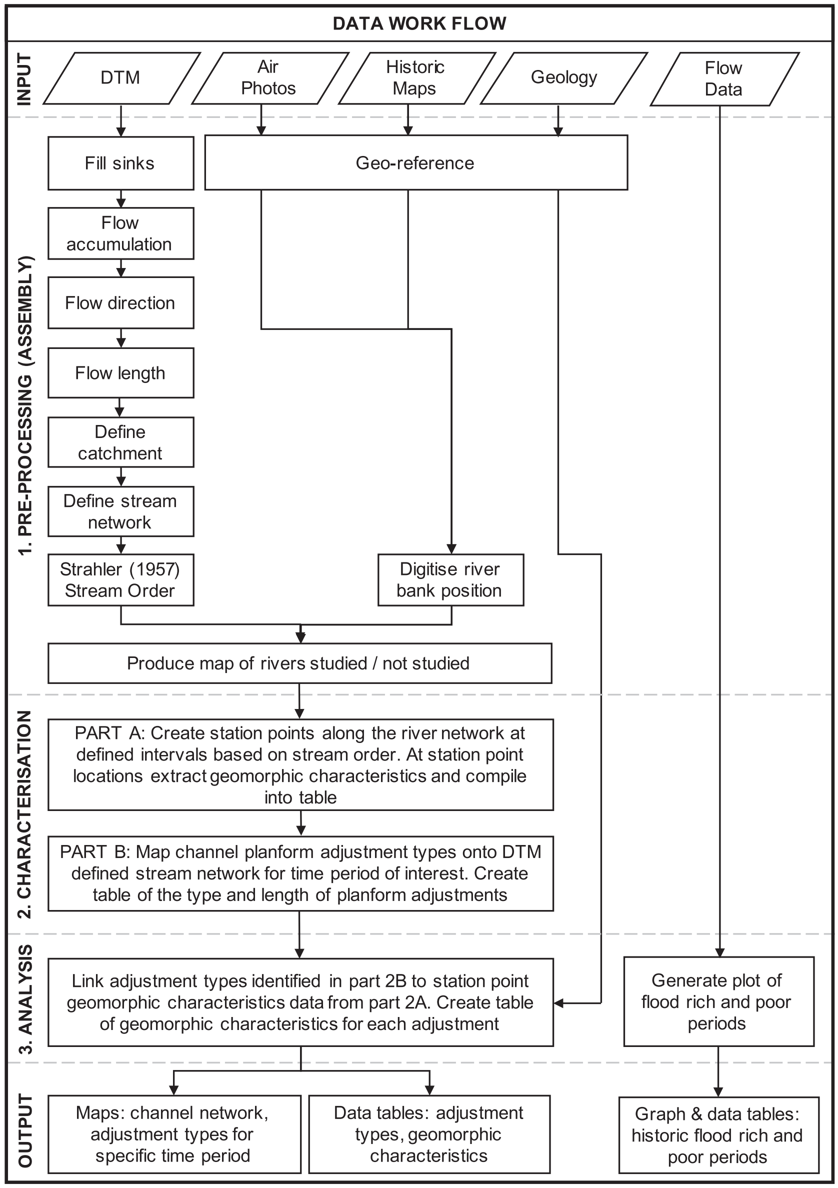

Fig. 1. Data requirements and GIS workflow for identifying and analysing planform adjustments, stable reaches and geomorphic variables. Part 1 involves manipulation of the DTM using GIS hydrology tools to identify the rivers and catchment typology. Part 2 involves identifying planform adjustments and 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

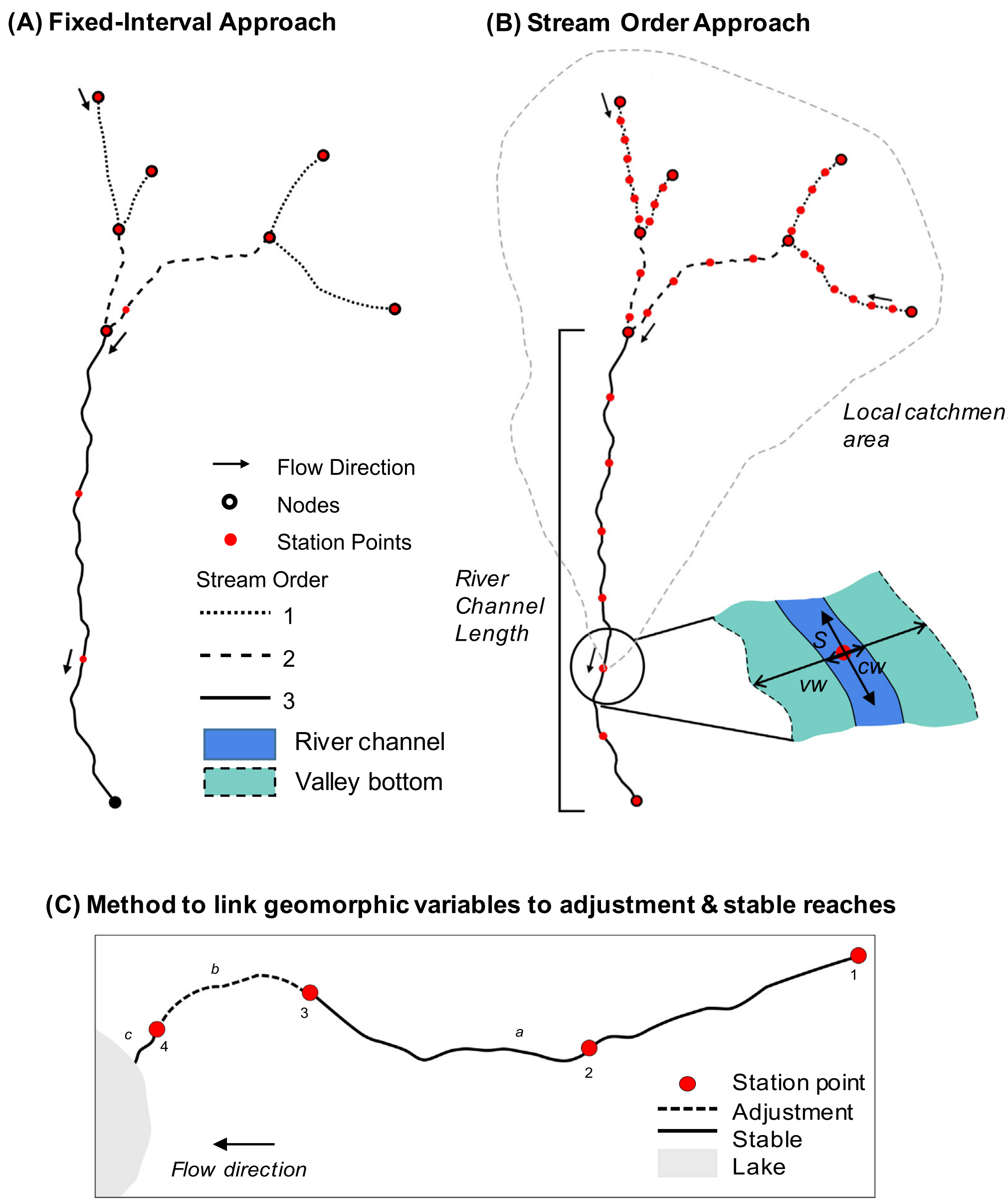

Fig. 2. Schematic of stream order channel start and end nodes and station point spacing intervals. (A) Example of 'fixed interval approach', a fixed SP interval distance often used on high order channels, applied to each stream order. (B) Example of SP intervals adjusted for each stream order and diagram 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):

$$\omega = \frac{\rho g Q S}{w} \tag{2}$$

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

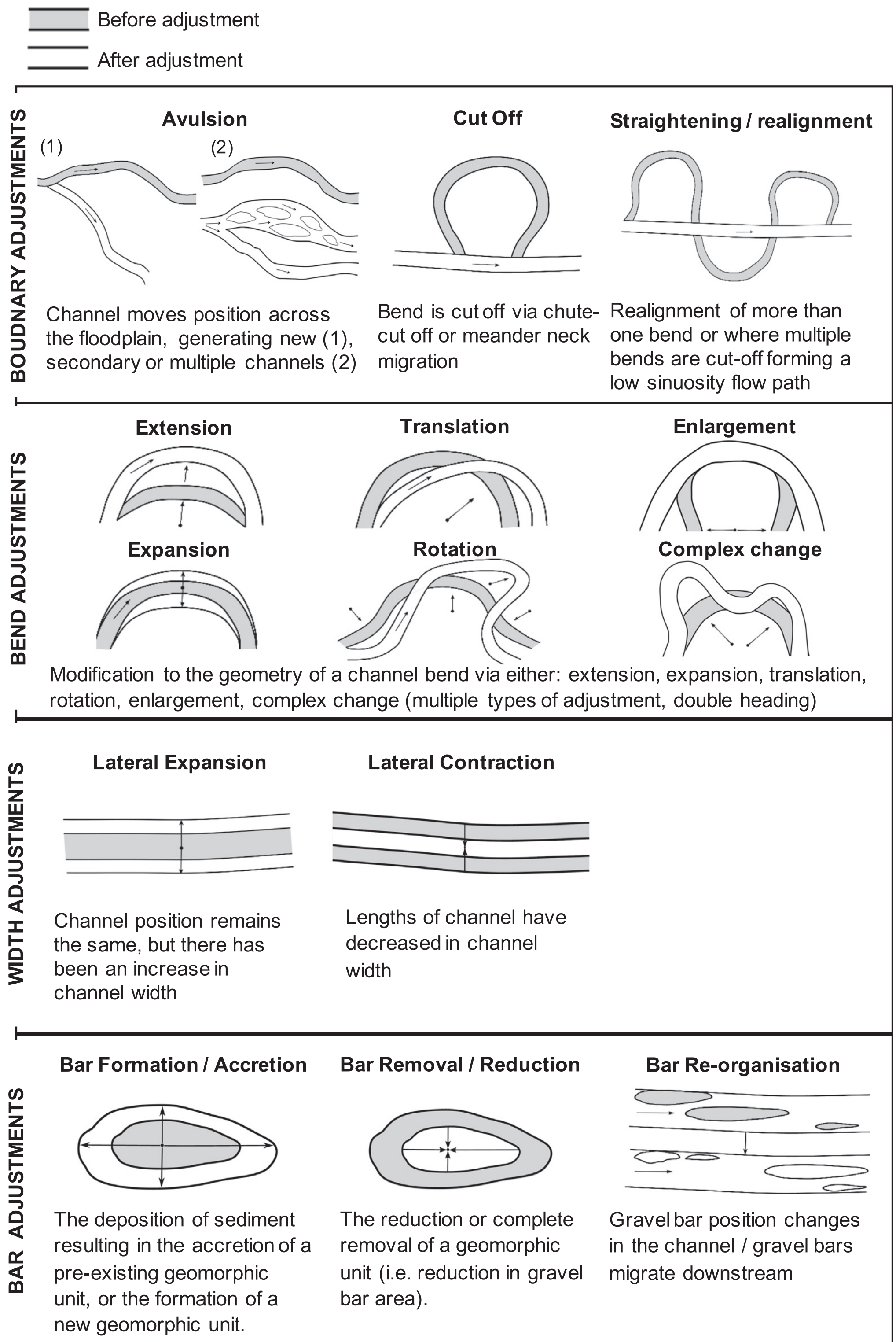

Fig. 3. Schematic of planform adjustment types and definitions adapted from Brierley and Fryirs (2005a, 2005b) and Fryirs et al. (2009).

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

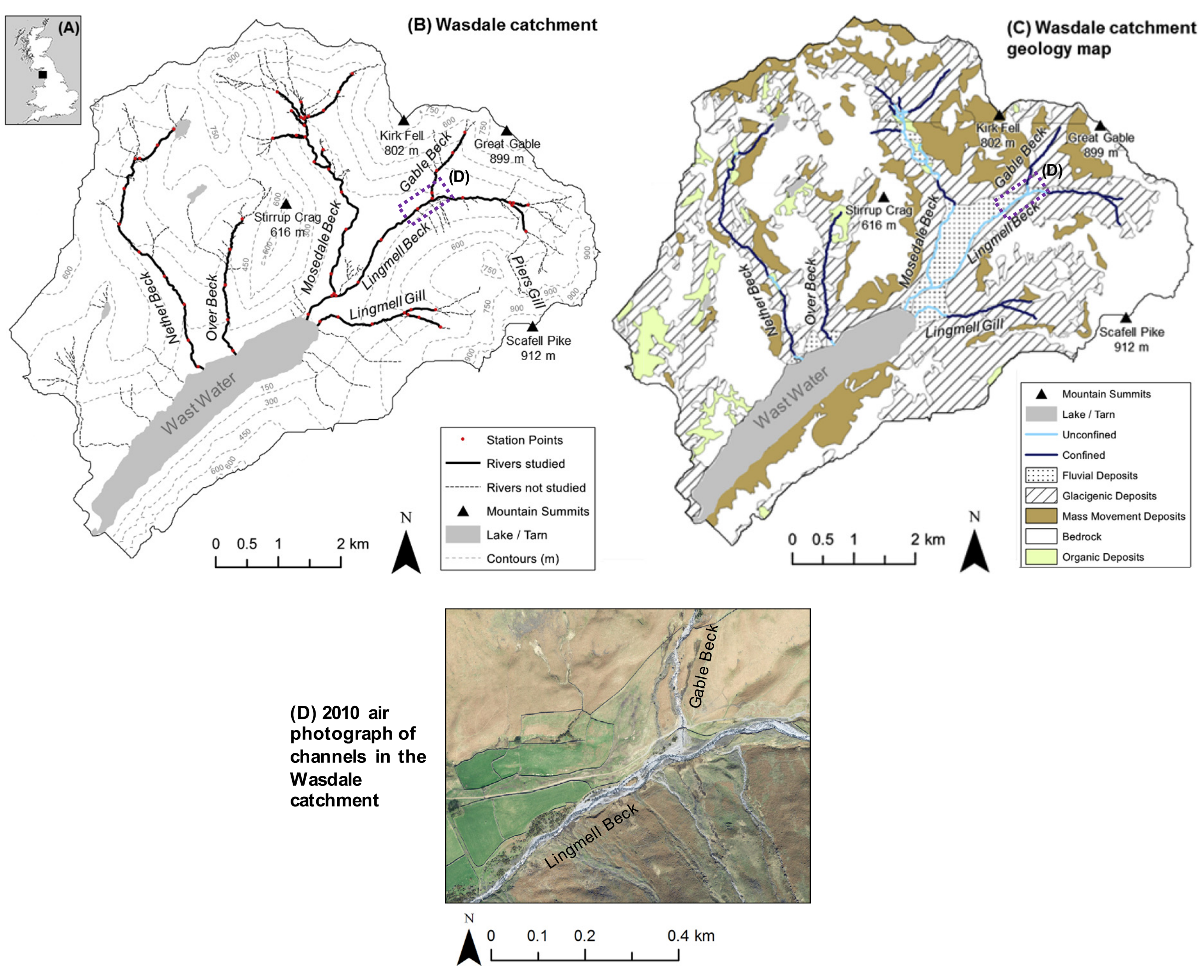

Fig. 4. (A) Location of Lake District upland region, north-west England. (B) Wasdale catchment study area (45.4 km^2) and channel network. Rivers not studied include those that are not identifiable from historic maps and air photographs (mainly first order channels). (C) Geology map of the Wasdale catchment 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

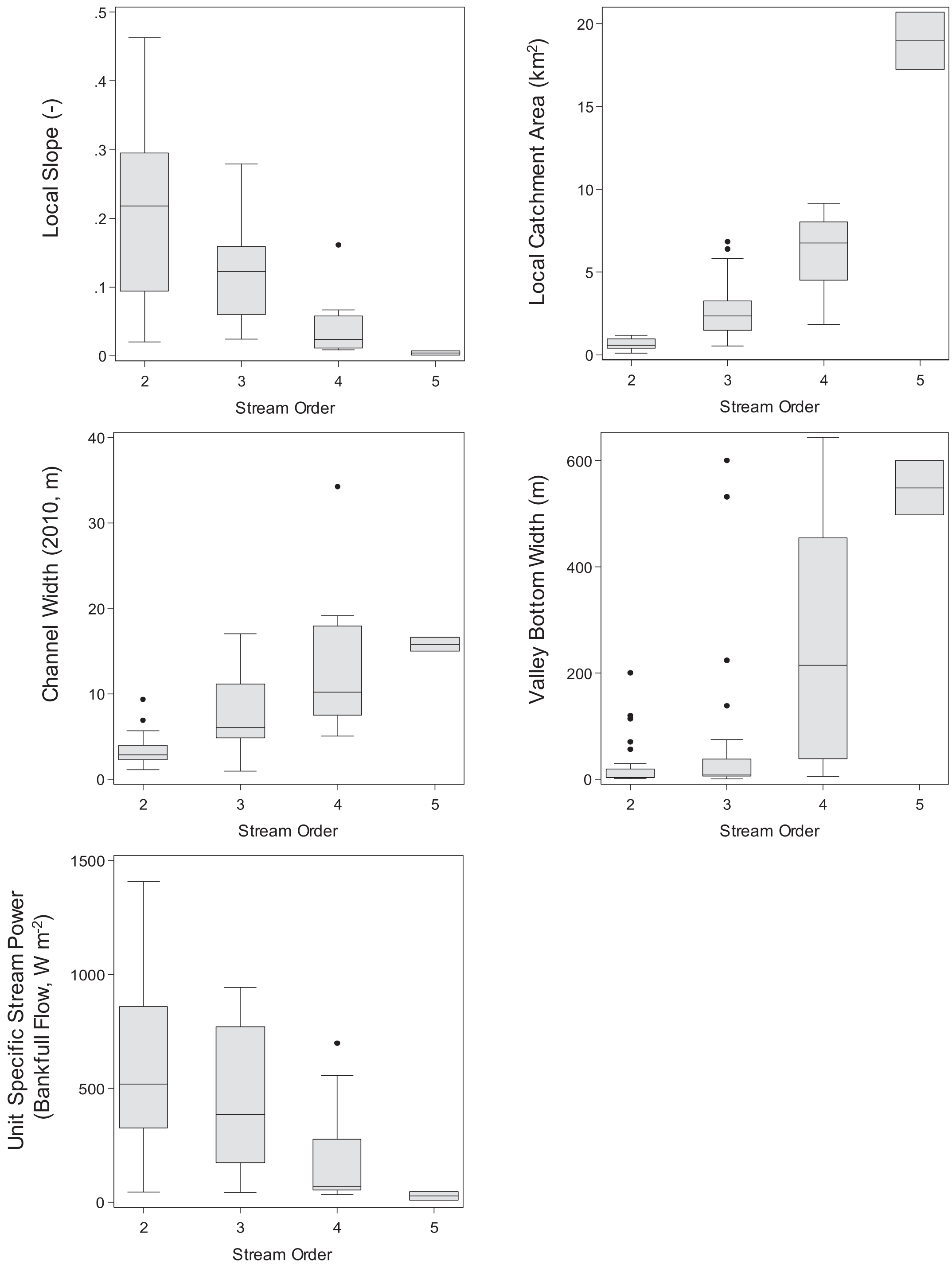

Fig. 5. Box plots showing the slope, catchment area, valley bottom width and unit specific stream power characteristics extracted from the station points for each stream order in the Wasdale catchment. Statistically significant differences were identified between the mean of the geomorphic variables 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

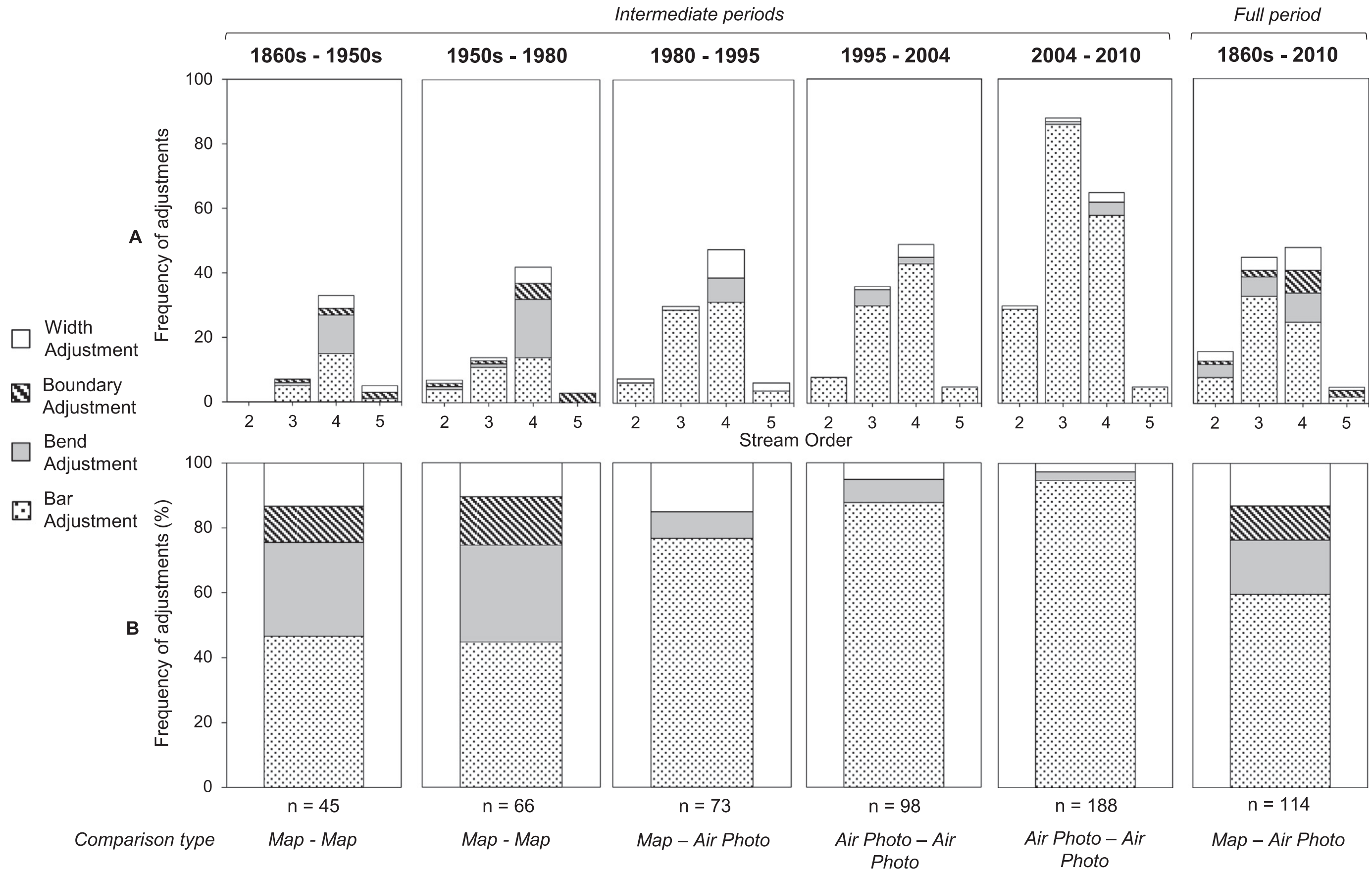

Fig. 6. (A) Frequency of planform adjustments by stream order, and (B) percentage frequency of planform adjustments in the Wasdale catchment, UK, for the available historical maps and air photographs (1860s – 2010).

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

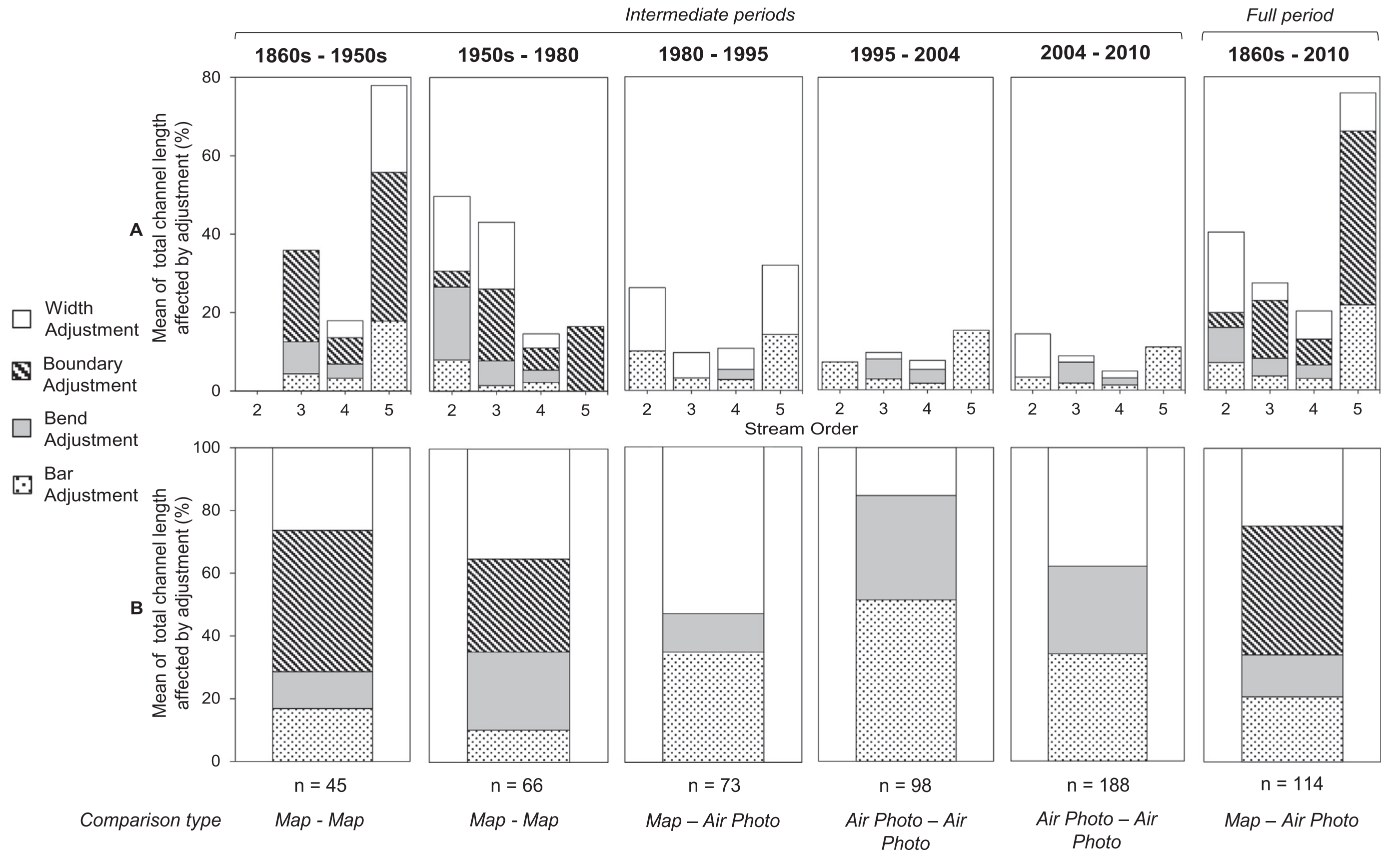

Fig. 7. Mean percentage of channel length affected by planform adjustment by stream order (A) and mean percentage of channel length affected by planform adjustment (B) in the Wasdale Catchment, UK, for the available historical maps and air photographs (1860s – 2010).

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

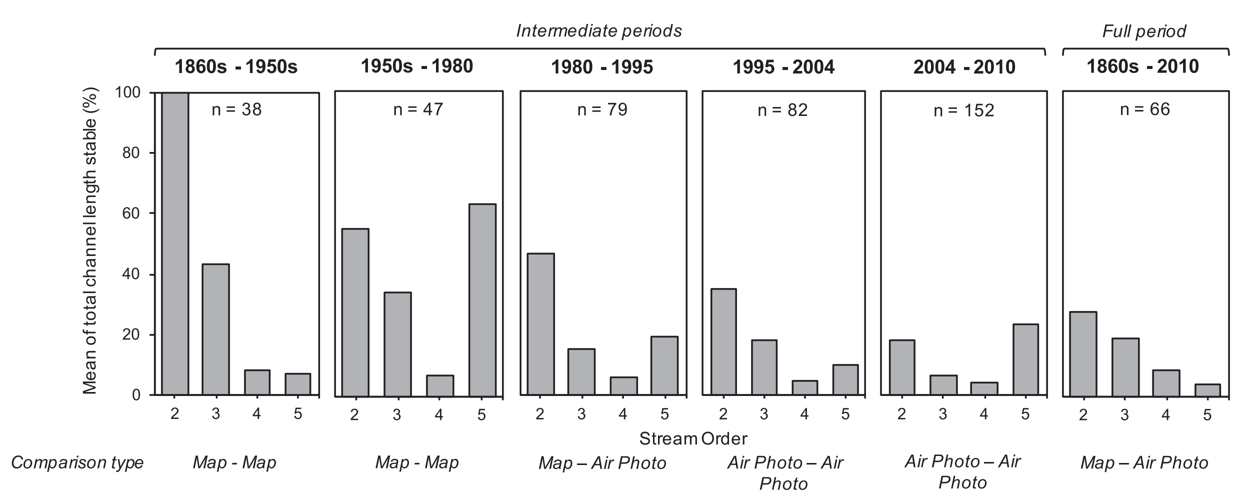

Fig. 8. Mean percentage length of stable reaches for each time period plotted against stream order for the Wasdale catchment, UK.

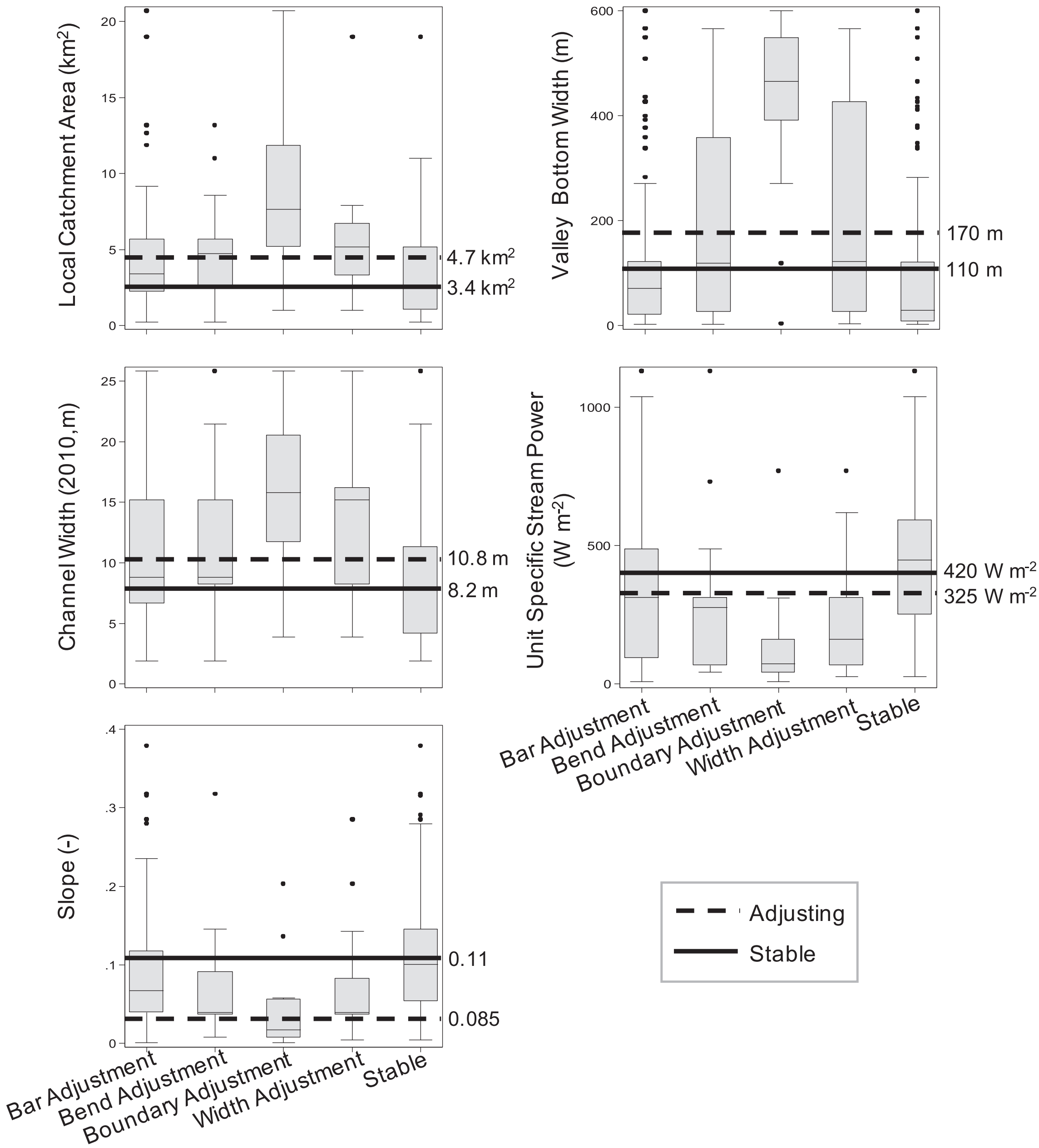

Fig. 9. Box plots showing the geomorphic variables for each planform adjustment category for all time periods. Continuous lines represent the mean geomorphic value for stable reaches, dashed lines indicate the mean geomorphic values for adjusting reaches.

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.

	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			•					•	•							•	•	•	•	•

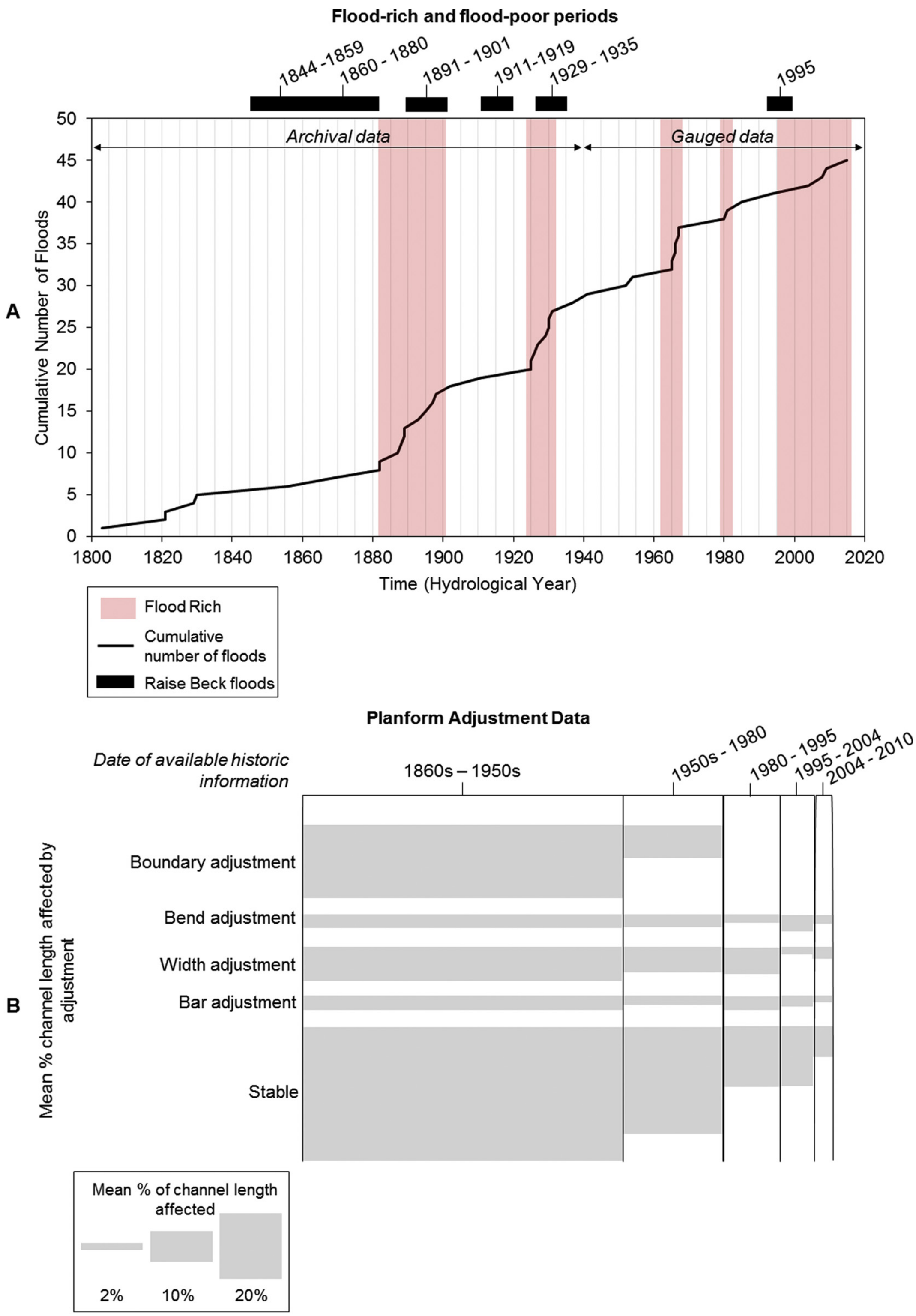

Fig. 10. (A) Cumulative number of high flow events as a function of time for the Lake District upland region. Peak flow data is based on documented extreme flood events from archival evidence and gauged data (19 gauges) that represent POT flows. Where the gradient of the line is steep it indicates a 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 $\pm$ 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 $\pm$ 110 m, allowing room for lateral planform adjustments. Lingmell Beck also had a low mean channel slope 0.03 $\pm$ 0.01, large mean catchment area 12 $\pm$ 1.7 km^2, and low mean stream power 130 $\pm$ 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

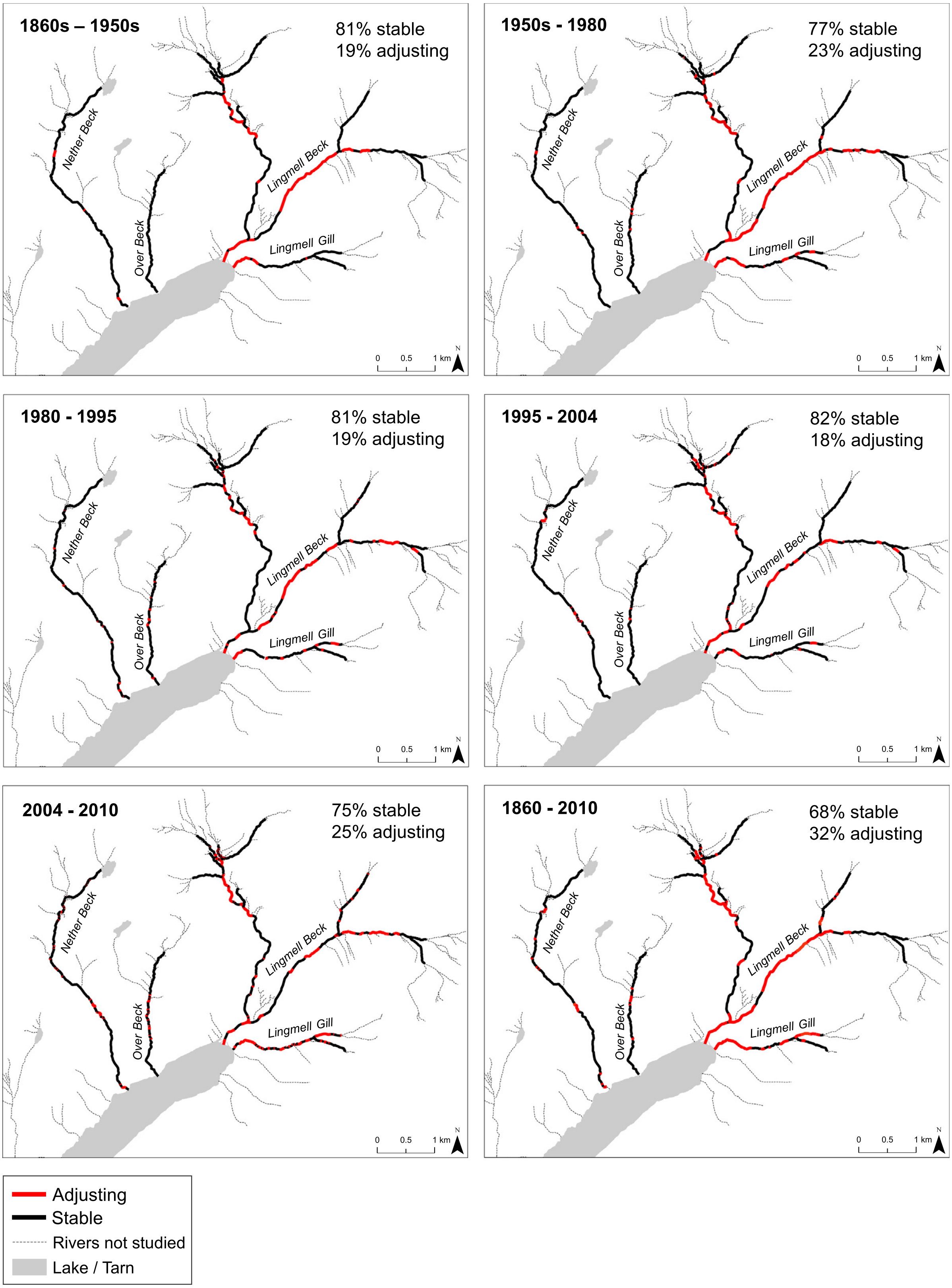

Fig. 11. Spatial pattern and percentage length of stable and adjusting reaches for all time periods of analysis in the Wasdale catchment, UK.

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

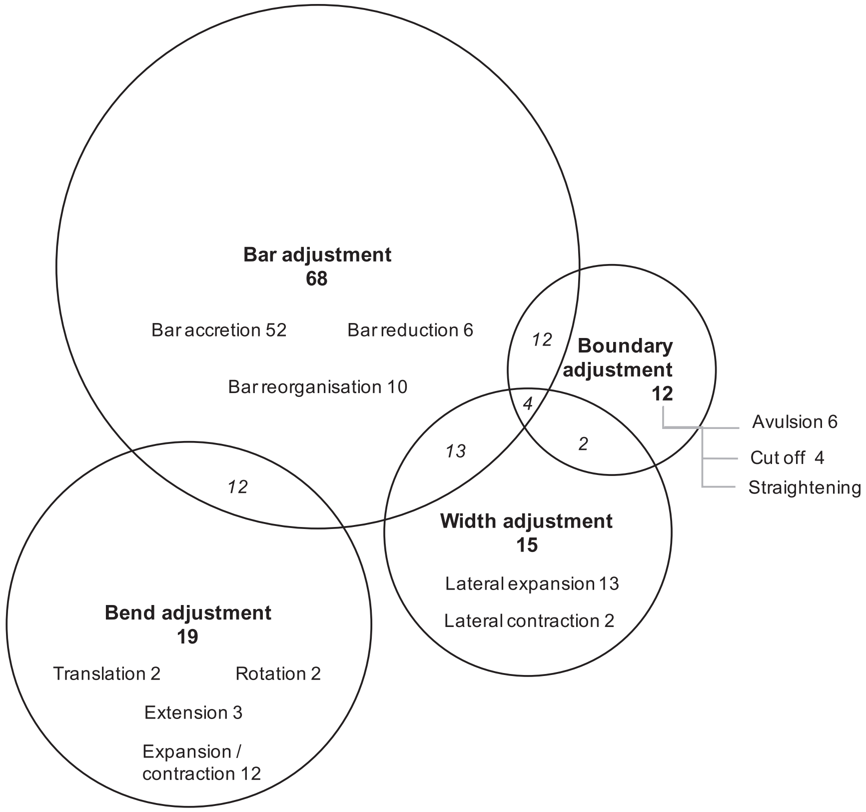

Fig. 12. Venn diagram showing the frequency of interactions between planform adjustment categories in the Wasdale catchment for the full period of analysis 1860s– 2010. Circles are proportional to the number of observed primary adjustments. Numbers in bold show the total frequency of adjustments for 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2020.107046.

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