Channel Change in the River Liza, Ennerdale, Cumbria:

An Examination of Planform Analysis

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1. Introduction

Planform is a commonly studied aspect of river systems, and planform change is usually measured through comparison of historical sources (typically maps and aerial photographs), although this approach can only detect relatively large-scale changes (Lawler, 1993). Long-term analysis of fluvial planforms may reveal whether fluvial system behaviour is in dynamic equilibrium or transitioning to a new state, which can elucidate the natural stability of channels and their sensitivity to natural and anthropogenic forcing (Downward *et al*., 1994; Large and Petts, 1996; Gurnell, 1997; Warburton *et al*., 2002; Jones *et al*., 2007). Such knowledge is essential for developing predictive river bank erosion models (Graf, 1984; Winterbottom and Gilvear, 2000), understanding local riparian communities (McVubbing *et al.*, 1998; Winterbottom, 2000), and informing appropriate land-use planning (Gurnell *et al.,* 1994; Gurnell, 1997; Harmar and Clifford, 2006). Compared with manual comparison methods, GIS analysis is advantageous in flexibility to utilise multi-modal datasets, processing speed, and uncertainty treatment (Downward *et al*., 1994; Winterbottom, 2000).

The River Liza in Ennerdale, Cumbria, was selected for investigation. Ennerdale is a classic over-deepened glacial valley in the western Lake District (Graham and Hambrey, 2007). Since 2003, the 'Wild Ennerdale' re-wilding project has been initiated in the valley, aiming to *'allow the evolution of Ennerdale as a wild valley for the benefit of people, relying more on natural processes to shape its landscape and ecology'* (www.wildennerdale.co.uk). The River Liza is considered a key component of Ennerdale's 'wildness' (National Trust, 2003), and therefore elucidating the natural behaviour and controls on this fluvial system is useful to inform appropriate re-wilding targets. Therefore, a desktop study was undertaken employing multi-modal/temporal GIS analysis of planform change between 1867-2009, in order to characterising the long-term behaviour of this dynamic gravel-bed/bedrock upland river.

The present analysis helps to explain the major spatial controls on fluvial planform, and although little progress was made with elucidating temporal controls on planform some potentially fruitful avenues for future research are identified. It is extremely important to understand the errors inherent in this approach (Lawler, 1993; Downward *et al*., 1994), and while Oyedotun (2011) previously investigated this system using the same approach, limited treatment of uncertainty in the previous study justifies critical re-evaluation to verify the previous inferences are appropriately substantiated.

Figure 1. Wild Ennerdale Study Area, Cumbria, UK. (Image contains public sector information licences under the Open Government Licence v1.0)

2. Methods

2.1. Study Area

The River Liza (54°30'N, 3°21'W) is a small upland gravel-bed/bedrock river, draining a ~26.3 km^2 catchment (derived from OS Profile 10 m^2 DTM using *Spatial Analyst>Hydrology* toolsets) which ranges in altitude from ~800 m to ~120 m a.o.d. The Liza flows into Ennerdale Water, a natural lake artificially raised by an outlet weir to increase water storage. The Ennerdale valley contains large quantities of glacigenic material (Hay, 1928; Jerram, 2004; Graham and Hambrey, 2007), contributing to high rates of geomorphic activity in at least some channel reaches (Oyedotun, 2011; Steve Carver, Pers. Comm.).

2.2. Data Acquisition and Preparation

Historic and contemporary maps and aerial imagery were obtained from Google Earth, and under licence from from EDINA Digimap (http://edina.ac.uk/digimap/) and the Wild Ennerdale project (www.wildennerdale.co.uk/gisdata.html), as indicated in Table 1. The 1840s Country Series OS maps are widely accepted as the earliest maps of sufficient accuracy to enable quantitative measurement of river planform (Lawler, 1993). Not all data was included in the present study, due to issues with spatial coverage, temporal duplication, uncertain dating, and insufficient quality and distortion in some aerial photographs (unused datasets are listed in Table S1, Supplementary Information). Analysis was undertaken in ESRI's ArcGIS desktop (V.10). All data were imported to the GIS using the British National Grid projection. Map tiles were mosaicked, and 2009 dGPS data were imported in decimal degree format and transformed from WGS_1984 to OSGB_1936 using the 7 parameter WGS_1984_to_OSGB_1963 petroleum re-projection.

Table 1. Datasets

Date	Description
2009	dGPS channel survey, conducted by T. Oyedotun, S. Carver, and J. Carrivick on 10^{th} of June, 2009. Latitude/Longitude/elevation for channel edges and 30 transects, global unprojected WGS84 ellipsoid, supplied by J. Carrivick, Pers. Comm.
'Modern OS' ~2012	OS 1:10,000 2012 Master Map dataset, probably based on an older map with 5-10 year revision of water features. Downloaded from EDINA Digimap © Crown Copyright.
2008	(Nonmetric) Colour Aerial Photograph. Acquired 10/05/2008. Downloaded from Google Earth. © Google Earth.
2003	(Nonmetric) Colour Aerial Photograph. Acquired 31/12/2003. Downloaded from Google Earth. © Google Earth.
1977	National Grid – First Metric Edition, Surveyed 1969-1977, Published 1977, Incomplete coverage (missing the lower reaches of the River Liza). Downloaded from WEPW © Crown Copyright.
1970s	(Nonmetric) Colour aerial photography of mart of the river valley. Downloaded from WEPW.
1956	National Grid - First Imperial Edition, Surveyed between 1948 and 1956, Published in 1956, 1:10,560 scale, downloaded from WEPW © Crown Copyright.
1867	Ordnance Survey County Series Map, 1^{st} Ed., Surveyed between 1846 and 1867, published 1867, 1:10560 scale, downloaded from WEPW. © Crown Copyright.

WEPW = Wild Ennerdale Project Website.

2.3. Data Co-Registration

To enable quantitative comparison, datasets were co-registered to the most recent OS 1:10,000 map, considered the most accurate base map, as relative accuracy is more important than absolute accuracy for geomorphological mapping (Jones *et al.,* 2007). Co-registration was undertaken using 10-24 Ground Control Points (GCPs) distributed across each image for optimal warp stability, using OS mapping grids and fixed man-made features such as building corners, with the same points used where possible for consistency (Leys and Werritty, 1999). Greater numbers of GCPs increases mathematical transformation error but are desirable because the overall transformation accuracy is improved and the influences of rouge points (discarded where identified) is reduced (ArcGIS Help, 2011). Although linear transformations are less susceptible to rouge control points, differential distortion of paper information during storage and scanning can necessitate the use of nonlinear transformations (Downward *et al.*, 1994). Maps and (nonmetric) aerial photographs were transformed using least squares 2nd and 3rd order polynomial transformations respectively, the later necessitated by greater distortion. Where more GCP were required for 3rd order transformations, these were concentrated along the river valley. Root Mean Square Error (RMSE) is one an indicator of transformation accuracy although low RMSE does not necessarily mean accurate co-registration, as higher-order transformations reduce RMSE but may increase image distortion greatly away from GCPs. The rectifying transformation resampled to 1 m^2 spatial resolution, employing nearest neighbour and cubic convolution resampling for maps and photographs respectively, for optimal detail retention (ArcGIS Help, 2011).

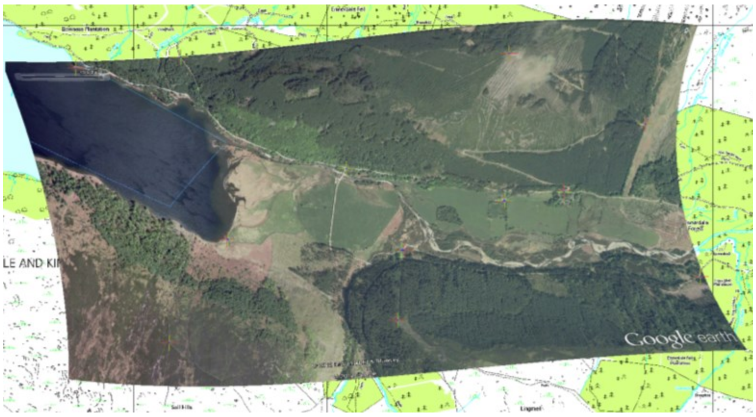

Figure 2. Co-referenced 2008 Google Earth aerial photograph overlain on the Modern OS basemap, following 3rd order polynomial transformation.

Table 2. Details of georectification transformations.

Data	n of GCPs	Transformation	RMSE
Modern OS Map		**Base Map**	
2008 Photo	12	3rd Order Polynomial	4.375
2003 Photo	14	3rd Order Polynomial	4.234
1977 Map	10	2nd Order Polynomial	2.516
1970s Photo 1	24	3rd Order Polynomial	15.359
1970s Photo 1	29	3rd Order Polynomial	16.354
1956 Map	10	2nd Order Polynomial	4.327
1867 Map	11	2nd Order Polynomial	4.776

RMSE = Root Mean Square Error.

2.4. Channel Digitization

Channel boundaries were digitised on-screen as vector polygons, with an upstream limit defined as where the modern OS map channel was depicted as a single line rather than two distinct channel boundaries. Defining channel boundaries is contentious. OS maps depict boundaries defined at the 'normal winter water level' (Harley, 1975), while interpreting channel boundaries from aerial images is complicated by variable river stage, particularly in braided reaches (Hooke and Redmond, 1989; Downward *et al*., 1994) and the vegetation edge boundary advocated by Winterbottom (2000) was adopted herein. All channel digitisation was undertaken by the same operator, aiding consistency, and unclear channel boundaries were interpolated where ≤~40 m and excluded if >~40 m.

2.5. Uncertainty in Historical Series Analysis

Using historical information to study rivers gives rise to a number of critical issues, referred to above, which while not precluding such approaches demands adequate consideration in order to develop substantiated inferences (Lawler, 1993). Maps are versions of reality, modified through both design and accident by the surveyor and the cartographer (Harley, 1975; Monmonier, 1996; Leys and Werritty, 1999), with demonstrated inconsistencies in past surveying of rivers (Hooke and Kain, 1982) (Figure 4). Although Lawler (1993) suggests more recent maps are more accurate depictions, Passmore *et al*. (1993) and Leys and Werritty (1999) found the 1st Ed. Country Series more accurately depict river channels than the later National Grid series maps. Furthermore, there is often confusion over map revision, confounding temporal assignment, with some uncertainty as to the 'normal' winter flow depth (Lawler, 1993). Further error is introduced during co-registration (Downward et al., 1994), and during channel digitisation (Gurnell *et al*., 1994; Leys and Werritty, 1999; Jones *et al*., 2007). Downward *et al*. (1994) quantified the later through statistical analysis of repeat digitising, reporting a digitising error of approximately ±2 m (P≤0.05) for a 1:10,000 scale map, although this is probably highly operator-dependent.

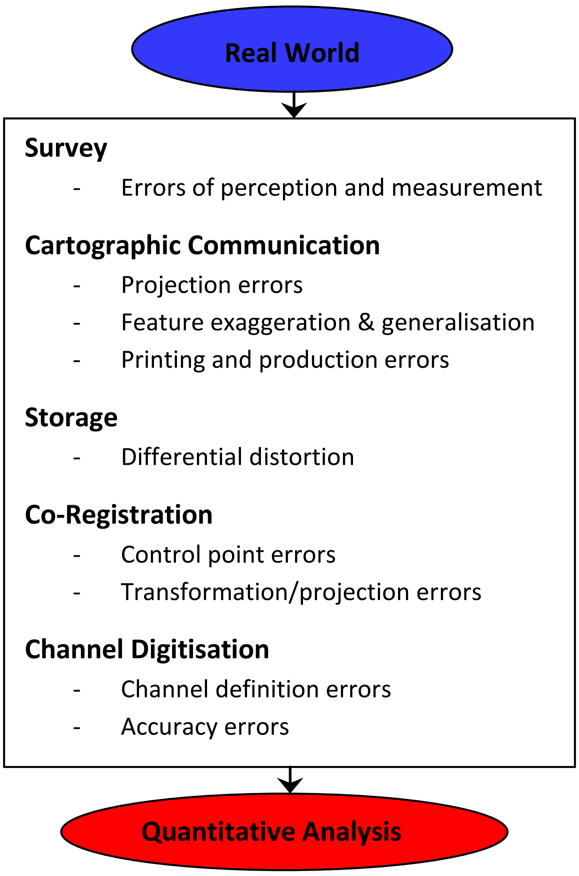

Figure 3. Sources of errors in GIS-based analysis of historical map sources (Adapted from Downward *et al*., 1994)

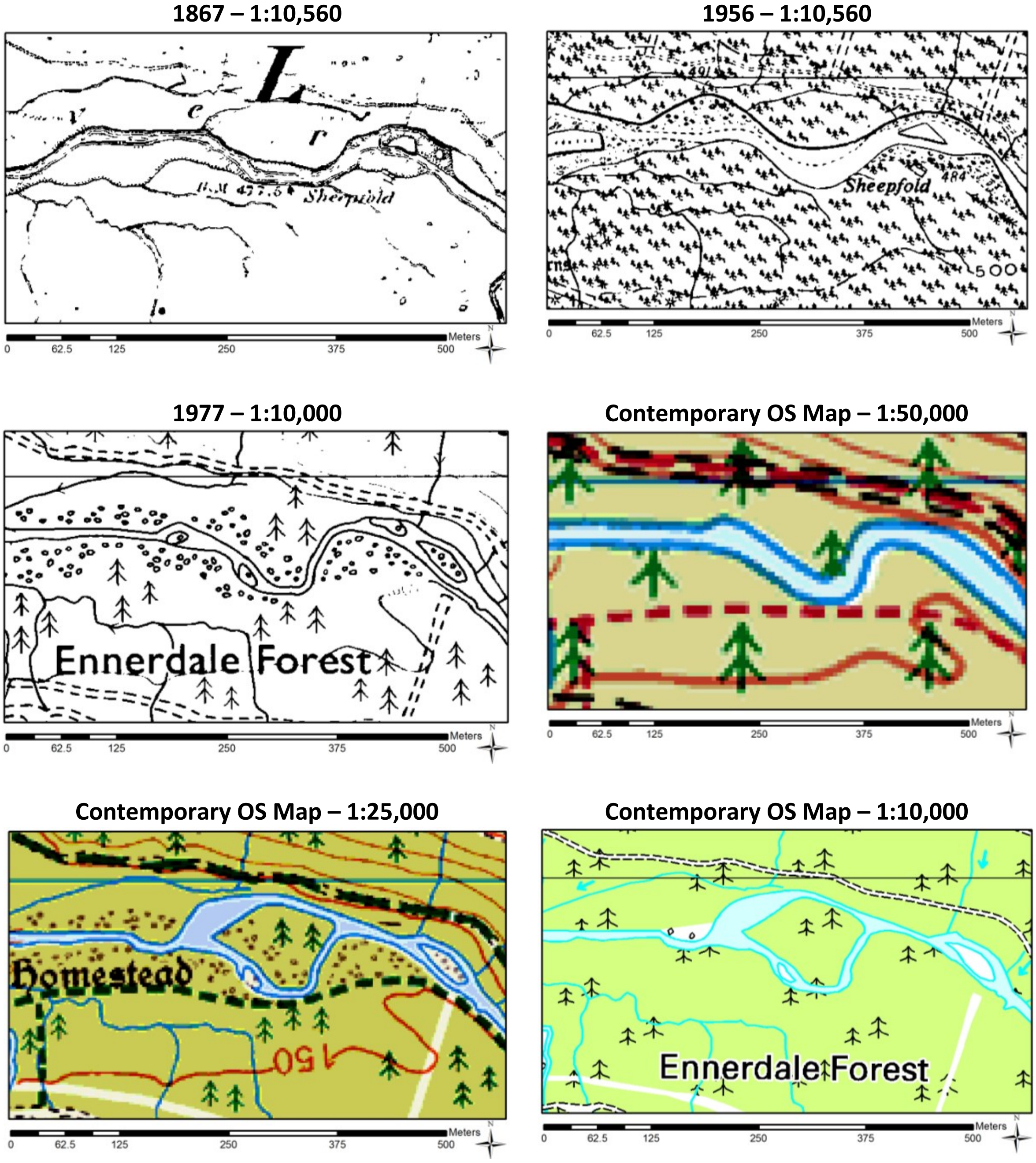

Figure 4. Cartographic inconsistences, the same subject area from all (georectified) map sources (NB. Contemporary 1:50,000 and 1:25,000 OS maps were not used for analysis).

Uncertainty analysis was performed to determine threshold distances for differentiating planform changes from analytical errors (Downward *et al*., 1994; Winterbottom, 2000). Original source error was assumed to be ±10 m for maps and photographs (1 mm at 1:10,000 scale) and ±0.2 m for the dGPS survey (J. Carrivick, Pers. Comm.), with georectification error taken from the RMSE of the transformation, and channel digitisation error was taken to be ±2 m after Downward *et al*. (1994). Ideally georectification error should be estimated using an independent set of GCP rather than those used to implement the transformation, however, insufficient suitable temporally stable features exist within the available coverage. All errors were assumed to be parametric and independent, with the total error of each dataset equal to the square root of the summed squared errors (Dr. Ian Vernon, Pers. Com). Thus, only if changes in channel boundary position between any two time periods exceed their ***combined*** total error (Table 3) can channel change be inferred. These uncertainties are large compared with most of the planform changes observed (Figure 5). Although channel width is a commonly reported planform metric (Leys and Werritty, 1999; Oyedotun, 2011), it is considered inappropriate given the size of the residual uncertainty. Sinuosity, the mid-channel length divided by the down valley length (Gurnell, 1997) and braid index, twice the total bar length divided by mid-channel length, (Brice, 1960, cited in Winterbottom, 2000) were calculated for each sub-reach. Channel occupancy maps were produced and qualitatively assessed, however, incomplete spatial coverage, irregular temporal sampling and variable boundary precision restricted their utility for the present exploratory study.

Table 3. Total Map Error.

Dataset	Total Error (m)
Modern OS	10.20
2009 dGPS	2.06
2008 Photo	11.10
2003 Photo	11.04
1977 Map	10.50
1970s Photo	18.85
1956 Map	11.08
1867 Map	11.26

3. Results

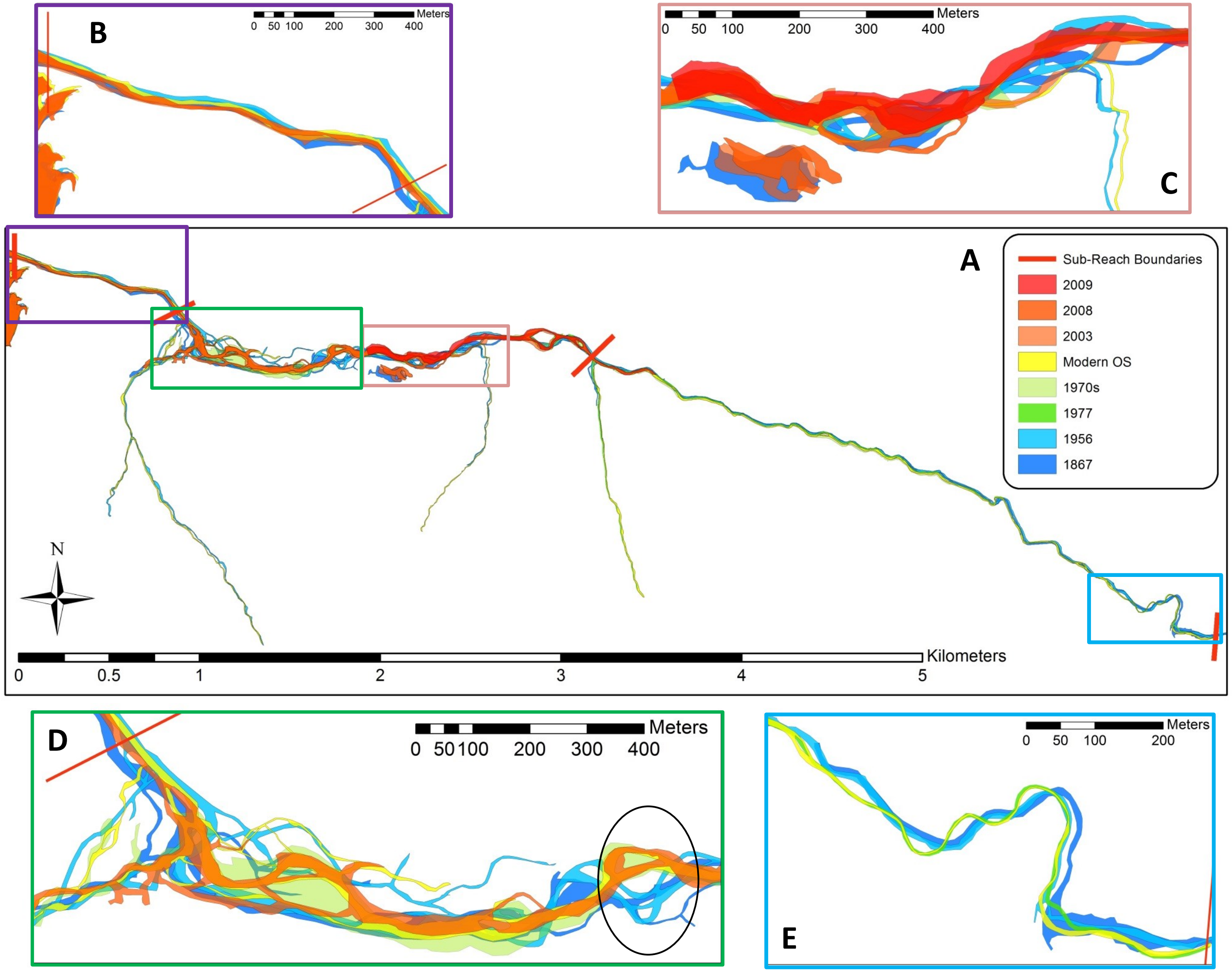

Figure 5. Digitised channel polygons, with red bars indicating (qualitatively assigned) sub-reach boundaries. Flow is from right to left. A) All eight time periods for all digitised channel; B) Sub-reach 3, a single-thread stable channel showing minimal temporal variability with no two time-periods showing channel changes greater than the total combined error other than at the very top of the sub-reach; C) a section of the wandering/braided gravel-bed sub-reach 2, with systematic offset of the tributary stream and geomorphically inactive lake indicative of final errors of ~12 m and ~17 m respectively; D) section of braided gravel-bed sub-reach 2 showing generally reasonable co-registration but with relatively high channel planform variability over the study period, a distinct avulsion is circled and discussed in text; E) Systematic offset suggests co-registration errors of ≤~25 m with the 1867 image although alignment between the 1956, 1977 and Modern OS maps is very good. Slightly increased meandering may represent actual planform change, but cannot be definitively inferred as changes are within the total error.

3.1. Sinuosity and Braid Intensity

Table 4. Sinuosity ratio and braid intensity in sub reaches.

		Sinuosity			Braid Index		
Time period	**Sub-Reach**	**1**	**2**	**3**	**1**	**2**	**3**
1867		1.14	1.13	1.05	0.000	0.811	0.000
1956		1.13	1.14	1.08	0.008	1.462	0.000
~1970s Photos		NA	1.13*	NA	NA	0.530*	NA
1977		1.16	NA	NA	0.000	NA	NA
2003		NA	1.19*	1.06	NA	0.421*	0.000
2008		NA	1.15*	1.06	NA	1.051*	0.000
2009		NA	1.08*	NA	NA	0.303*	NA
Modern OS Map		1.16	1.13	1.06	0.064	1.010	0.000
n of complete coverages		4	3	5	4	3	5
Range of complete coverages		1.13-1.16	1.13-1.14	1.05-1.08	0.00-0.06	0.81-1.46	0.00-0.00

***incomplete spatial coverage, therefore directly comparable with other time steps. NA = no coverage of that sub-reach at that time period.**

4. Discussion

Planform analysis reveals a number of spatiotemporal characteristics of the fluvial system, although inferences are significantly weakened by uncertainty. Three distinct sub-reaches were qualitatively identified: 1) a single-thread fairly stable channel running 4.39 km from NY192123 to NY157138; 2) a wandering/braided gravel-bed channel continuing 2.64 km downstream to NY134131; and 3) a very stable 0.99 km single-thread channel down to the river mouth as NY125134. Sinuosity ranged between 0.13-1.16, 1.13-1.14, and 1.05-1.08 in sub-reaches 1 to 3, respectively (only datasets with complete spatial coverage), though low for natural channels, these values are typical of wandering gavel-bed rivers (Winterbottom, 2000). Braid index varied between 0.00-0.06, 0.81-1.46, and 0.00 in sub-reaches 1 to 3, respectively. Braid index is particularly susceptible to methodological error, as seasonal variations in vegetation extend influence island delineation in aerial photographs in addition to potential inconsistencies in cartographic representation. Sub-reach 2 displays a very strong cyclicity in braid intensity through all 7 time-periods, although only 3 of these periods have complete coverage. Locations showing apparent change but believed to be stable (for example, Figure 5C) have differences less than the total combined error.

It is challenging to definitively assign controls on fluvial system behaviour (Hooke and Redmond, 1992), however, the primary control on the spatial patterns of the three distinct sub-reaches appears to be topography (Figure 6). Sub-reach 1 is mostly bedrock channel (Graham and Hambrey, 2007; Steve Carver, Pers. Comm.) in a narrow upper valley, effectively determining the river's course and planform (*cf*. Brewer and Lewin, 1998). Although there is a possible increase in meandering (shown in Figure 5E), the observed changes are within the combined error of these datasets and therefore cannot be reliably inferred. The beginning of sub-reach 2 coincides with a widening of the valley, de-constraining the river and enabling the storage of large quantities of gravel deposits (indicated on maps and photographs). Together, these facilitate a relatively active geomorphology. Through the ~140 year study period, sub-reach 3 is extremely stable with no in-channel bars indicated on any maps or photographs. This temporal stability may be largely due to the Woundell Beck alluvial fan, which (Hey, 1928) suggests forced the River Liza to its present course along the northern edge of the valley, although on the basis of bathometric survey of Ennerdale Water, Mill (1895) suggests the Liza's mouth was south of its present location sometime before 1770. Engineering works around bridges can significantly restrict natural channel change (Leys and Werritty, 1999), and at least one of the two bridges across sub-reach 3 is surrounded by significant hard-engineered bank-stabilisation (Figure 8), which greatly restricts natural channel migration at this location. The single bridge across sub-reach 1 occurs well above the water level where the channel is incised into bedrock (Steve Carver, Pers. Comm.), and therefore is expected to exert minimal influence on the fluvial system. Further elucidation of topographic controls on this fluvial system could be facilitated by topographic survey to explore relationships between channel slope and planform/channel stability (Knighton, 1998).

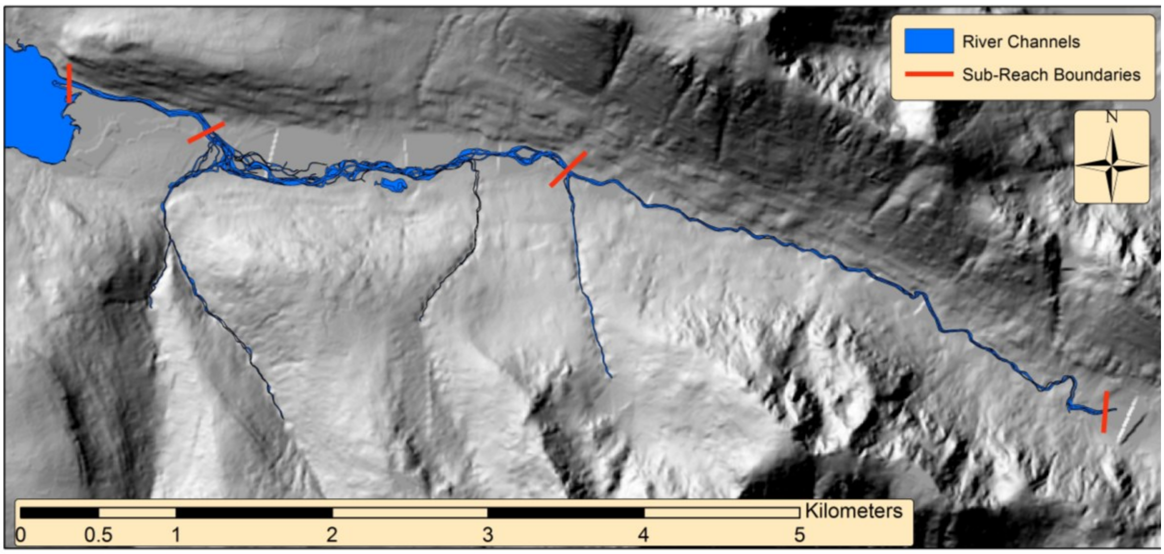

Figure 6. topographic constraint. Hillshade derived from the 10 m^2 OS Profile DTM, using an Azimuth of 315°, Altitude of 45° and 2 times vertical exaggeration to attenuate topography.

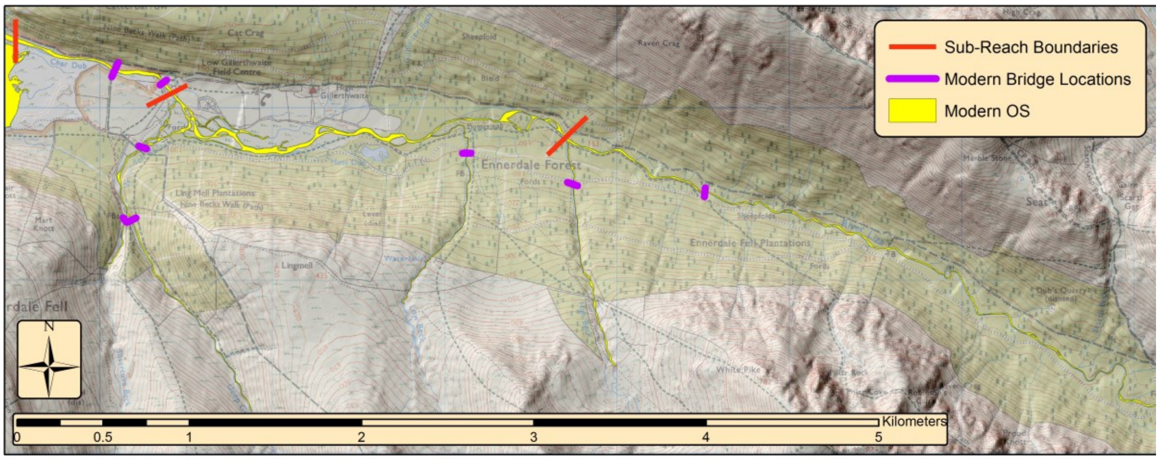

Figure 7. Modern bridges locations around the River Liza, with the Modern OS river channel, sub-reach boundaries, and 1:25,000 OS map overlain by a semi-opaque hillshade for context.

Figure 8. Looking upstream at Irish Bridge crossing the River Liza. Irish Bridge is the furthest downstream bridge, situated within sub-reach 3, and post-2000 river bank erosion defences are shown in the foreground (photograph from www.glowingcoast.co.uk/lakedistrict/whs/pics/ennerdale/01.htm on 27/04/2012).

Although a number of shifts in channel boundary position exceeded the combined total error occurred, processes inference (*i.e.* assigning channel locational changes to lateral erosion or avulsion) is challenging (Brewer and Lewin, 1998), particularly in the absence of ground observations, and assumptions regarding continuity and linearity of changes are often required (Lawler, 1993). Some channel movements appear to be reoccupation of previous channels via avulsion rather than lateral erosion, for example, Figure 4 which shows a probably avulsion between 1977 and 2003 to a historic channel inferred from streamline in the 1867 map, with both the northern and southern channels remaining occupied in all subsequent periods. Figure 5D (circled area) shows another channel migration between 1956 and the 1970s photograph, although it is not possible to confidently determine the mechanism of channel location change. High rates of channel planform change are often associated with abnormally high flows (Leys and Werritty, 1999; Winterbottom and Gilvear, 2000; Passmore and Macklin, 2000) with numerous studies demonstrating that major flood(s) can decrease channel sinuosity (Knighton, 1998), although Warburton *et al*. (2002) found that floods do not necessarily modify channel planform in gravel-bed rivers. Investigation of the relationship between planform change and discharge is not currently possibly, because the River Liza is, and will remain, ungauged. However, an estimated discharge record could be inferred from precipitation data using standard methodologies as detailed in the CEH's Flood Estimation Handbook (1999). The Environment Agency has three rain gauges within the Liza's catchment, and numerous surrounding ones which can facilitate spatial interpolation of rainfall data since at least 1994 (Susan Sandelands, EA Hydrometry Officer, Pers. Comm.). Within the present analysis it is impossible to determine whether there has been any change in the River Liza as a result of the Wild Ennerdale project initiation in 2003, although considering the small changes in land-use and the fact that the valley has only been subject to low-intensity land-use since the Bronze Age (National Trust, 2003) means significant changes are not anticipated.

The present analysis is supports Oyedotun's (2011) finding that planform change is highly variable between sub-reaches, probably due to topographic spatial-controls (*cf.* Leys and Werritty, 1999). The most significant changes in channel planform (in sub-reach 2) occurred between 1977-2003, which again concurs with Oyedotun's (2011) claim that the River Liza was very stable other than between the period 1993-2009. Utilising more datasets (particularly aerial photographs) than those utilised herein, Oyedotun's study offered higher temporal resolution. While this could produce slightly different results from the present study, Oyedotun's (2011:260-261) claim "…that the River Liza is a very dynamic river with changes in channel occupancy, channel width and direction…" is disputed. In the present analysis, over three quarters of the channel considered did not move significantly (more than the combined total error of any two datasets), so such statements should be spatially constrained to the active reach (sub-reach 2 in the present study). Oyedotun discussed decimetre-scale (0.1 m) changes in channel width, however analysis of historical maps and nonmetric aerial photographs only offers precision at meter-scales at best and the present study found precision to be on the order of decametres (10 m). Oyedotun (2011) does not report any uncertainty from map sources, co-registration, or channel digitisation, and assessment of channel width changes from these datasets for this river channel is considered inappropriate. Furthermore, changes in flow direction cannot be reliably inferred from analysis of historical maps or coarse-resolution aerial photographs. Oyedotun (2011) states the 2009 dGPS survey is accurate to 1 cm, but fails to report measurement precision (approximately ±0.1m and ±0.2m in the horizontal and vertical respectively, Dr J. Carrivick, Pers. Comm.). Oyedotun asserts that, although there are a number of human features influencing the fluvial system, particularly bridges, natural processes shape its course along most of the river channel, which can be considered a "…natural laboratory for fluvial processes." (2011:261). Although claim cannot be reliably examined solely through desktop study, it can perhaps be considered as immoderate, particularly if spatially unconstrained.

The following research avenues are recommended to support future efforts to understand the River Liza as a hydrogeomorphological system. The additional datasets, listed in Table S1, should be acquired and imported to the GIS to both increase temporal resolution and in the case of duplicate temporal coverage facilitate accuracy assessment(s). The errors inherent in each map source should be more accurately described in order to quantify total error. Further investigation of data lineage may be appropriate, particularly with regards to survey and revision dates of map sources. Derivation of a discharge record from precipitation data as outlined above would be valuable for investigating temporal controls on the River Liza's planform. It may be appropriate to describe planform changes in the complex braided sub-reach 2 in terms of $m^2\ m^{-1}\ yr^{-1}$ rather than $m^{-1}\ yr^{-1}$ (Leys and Werritty, 1999). There is significant potential for high temporal-resolution analysis of changes in sub-reach 2, for example, using an Unmanned Aerial Vehicle (UAV) for annual or even sub-annual survey, particularly if an estimated discharge record can be derived, although higher-temporal resolution datasets increases problems with assigning smaller differences in channels boundaries as change rather than errors in the data transcription process (Gurnell *et al.*, 1997).

5. Conclusion

In conclusion, a desktop-GIS analysis of channel planform change in the River Liza was undertaken using historical maps and aerial photography. Three distinct sub-reaches were identified on the basis of planform stability, with topographic constraints of valley floor width and a tributary's alluvial fan apparently being the primary spatial controls. There was a high degree of uncertainty, stemming from the original maps, co-registration, and channel digitisation, which severely restricted the type of quantitative analysis that could be appropriately undertaken. Importantly, inappropriate treatment of this uncertainty in previous studies may undermine several prior conclusions. In particular, the claim that the River Liza is highly dynamic should be spatially constrained, as over three-quarters of the river channel appear to be highly stable through the 140 year study period. Further planform analysis of this small river channel using poor-precision datasets is unlikely to advance understanding of the River Liza fluvial system, although acquisition of additional dGPS surveys and/or high-spatiotemporal resolution monitoring could be very valuable, particularly if an estimated discharge record can be inferred from precipitation data and validated with spot gauging.

6. Acknowledgements

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8. Supplementary Information

Table S1. Other Available Data Sources.

Date	Description
1995	Black and White (Nonmetric) aerial photographs. Ordnance Survey Contact Prints of the upper 4km of Ennerdale valley, Dr Dave Graham, Pers. Comm. (D.J.Graham@lboro.ac.uk)
1993	Black and White (Nonmetric) aerial photograph, ~1:10,000 scale, taken on 23/05/1993. Forestry Commission, Northwest Forest District (Used by Oyedotun, 2011).
1985	Black and White (Nonmetric) aerial photograph, ~1:10,000 scale, taken on 02/06/1985. Forestry Commission, Northwest Forest District (Used by Oyedotun, 2011).
1978	National Grid – Latest Edition Historical map, published in 1978, 1:10,000 scale.
1970s	Two black and white Forestry Commission (Nonmetric) aerial photos, available from the Wild Ennerdale Project website (www.wildennerdale.co.uk/gisdata.html).
1900	Ordnance Survey County Series Map, 2nd Ed (1:10,560 scale). Inexplicably absent from the EDINA Digimap Archive
Post-2000	Likely to be LIDAR coverage obtained as part of ongoing Environment Agency flood map surveying (2m spatial resolution, vertical precision better than ±0.25m), the utility of which for geomorphological mapping was demonstrated by Jones *et al*. (2007).
???	Military Aerial Photography – write to Pre-1971: 'The Aerial Photographs Unit, Royal Commission for Historic Monuments, 19 Fleming Way, Swindon, SNl 2NG', post-1971: 'Aerial Photograph Advisory Service, Room N 09, Ordnance Survey, Romsey Rd, Maybush, Southampton SO9 4DH.' enclosing a copy of the relevant 1:50,000 OS. map clearly marked with the area of interest.

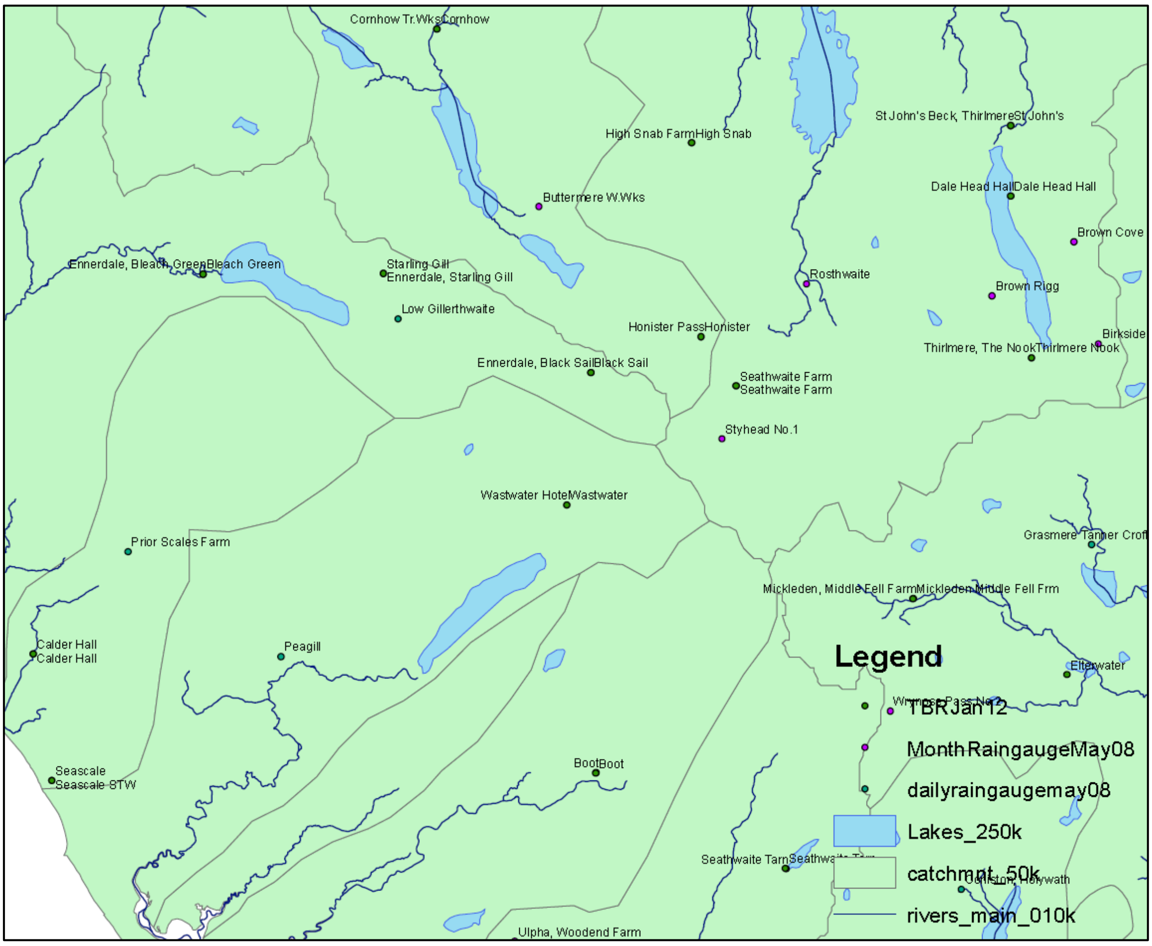

Figure S1. EA precipitation gauges around the River Liza catchment. (Map provided by Susan Sandelands, EA Hydrometry Officer, 2012)