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The geomorphology of the River Tyne at Clerkington Weir, East Lothian

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ENGINEERING GEOLOGY AND INFRASTRUCTURE PROGRAMME
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The geomorphology of the River Tyne at Clerkington Weir, East Lothian

Andrew Finlayson, Chris Thomas, Katie Whitbread

Keywords

weir, geomorphology, sediment, channel evolution.

National Grid Reference

SW corner 350330,671850
Centre point 350610,672350
NE corner 351000,672620

Map

Sheet Scotland 33W, 1:50 000 scale, Haddington

Front cover

View across Clerkington Weir looking north.

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Foreword

This report describes a geomorphological study on the River Tyne at Clerkington Weir, East Lothian, undertaken by the British Geological Survey (BGS), as part of the Alan Turing Institute's *Modelling Resilience of Aging Structures* project. The work described here was jointly funded by the BGS' *GoForth* project (Engineering Geology and Infrastructure Directorate), and by the Lloyds Register Foundation and Models 2 Decisions Network, through the Alan Turing Institute.

Acknowledgements

This geomorphology report forms a contribution to a larger project, which was initiated by Dr Victoria Stephenson (Bath University) and Dr Chris Oates (Alan Turing Institute), both of whom are thanked for valuable discussions relating to the topics discussed here. Clerkington and Lennoxlove estates are thanked for allowing access during this field study. Tim Kearsey is thanked for reviewing an earlier version of this report.

Contents

Foreword i

Acknowledgements i

Contents i

1 Introduction 4

2 The Site 4

2.1 River Tyne Catchment 4
2.2 Local Setting 7

3 Historical River Change 10

4 GPS Survey 12

5 Derived river characteristics in the vicinity of Clerkington Weir using the 28th September 2018 GPS data. 14

6 Discussion 19

6.1 Influence of the weir on the river 19
6.2 Likely evolution following weir loss 19

7 Recommendations for further work 20

References 21

FIGURES

Figure 1. A. Location of the Tyne catchment in south-east Scotland. B. Catchment relief and stream network. Hill-shaded and coloured relief model based on UK Perspectives elevation data © UKP/Getmapping Licence No. UKP2006/01. Numbers refer to gauging stations: 20007 = Coulston Water at Lennoxlove, 20006 = Birns Water at Saltoun Hall, 20003 = Tyne at Spilmersford, 20001 = Tyne at East Linton. 5

Figure 2. A. Elevation profile of the main branch of the river Tyne, with the position of Clerkington Weir shown. B. Contributing drainage area along the main branch of the river Tyne. 6

Figure 3. Drainage area-discharge relationships from gauging station data for (A) mean flow over the total station recording period and (B) maximum peak flow from the water year 2000-2001. 1 = Beil Water, 2 = Coulston Water at Lennoxlove, 3 = Birns Water at Saltoun Hall, 4 = Tyne at Spilmersford, 5 = Tyne at East Linton. 6

Figure 4. A. Aerial photograph (2009) of the study site around Clerkington Weir. RGB Aerial Photography © GeoPerspectives. B. Hill-shaded and coloured relief model of the study site, based on UK Perspectives elevation data © UKP/Getmapping Licence No. UKP2006/01. ... 7

Figure 5. Shallow geological and geomorphological map of the survey area. 8

Figure 6. Sediment logs from 2 exposures along the riverbanks. Locations are shown in Fig. 5.. 9

Figure 7. Size distribution of grains on the gravel river bed taken from three bars. The locations of the bars are shown on Fig. 5. 10

Figure 8. Changing channel centreline positions from the period 1855-2018, derived from historical Ordnance Survey maps, dated aerial photographs, and a recent GPS survey. RGB Aerial Photography © GeoPerspectives. 11

Figure 9. The lower weir (approximately 400 m downstream from Clerkington Weir), which was previously covered by alluvium, and has once more become exposed by channel migration. 12

Figure 10. Plot of river bed (red) and water surface (blue) elevations from GPS data. 12

Figure 11. A. Plot of water depth along the surveyed profile. RGB Aerial Photography © GeoPerspectives. B. Graph showing water surface elevations and river bed elevations along the survey profile. 13

Figure 12. Graph showing river width along the surveyed profile. 14

Table 1. Slope trends along surveyed reaches of the river Tyne 14

Figure 13. A. Plot of calculated basal shear stress along the surveyed profile. RGB Aerial Photography © GeoPerspectives. B. Graph showing basal shear stress values along the same profile. 15

Figure 14. A. Plot of calculated mean velocity along the survey profile. RGB Aerial Photography © GeoPerspectives. B. Graph of calculated mean velocity for an assumed rectangular channel (black line) and ‘v-shaped’ channel (blue line). 16

Figure 15. Graph showing different calculations for discharge through the survey area. Black dots show the scatter in calculated discharge at the long profile survey points (described in text) highlighting, amongst other factors, uncertainty in knowledge about channel cross sectional geometry. The black line shows the trend of these values. The blue line shows the

discharge values calculated from the mean flow area-discharge relationship derived from catchment gauging station data..17

Figure 16. A. Plot of stream power along the survey profile. RGB Aerial Photography © GeoPerspectives. B. Graph showing stream power calculations obtained using different approaches. The dots show values derived from the long profile survey. The red line is derived using the discharge trend obtained from the survey points. The blue line is derived using the drainage area-discharge relationship. The green line represents stream power values that might be expected under a more evenly graded river if the surface slope was constant along 970 m-long profile...18

TABLES

Table 1. Slope trends along surveyed reaches of the river Tyne..14

1 Introduction

The British Geological Survey was invited by colleagues from the Alan Turing Institute and the University of Bath to contribute to a multi-disciplinary pilot study, which aims to help reduce uncertainty when considering the resilience of historic engineered structures in rivers. Many such structures in UK rivers are at significant risk of collapse due to their age and declining condition resulting from lack of maintenance. In recent years, a number of these structures have failed unexpectedly during flood events, often with severe consequences for the surrounding natural and built environment.

Engineers, planners and policy makers are required to consider the risk associated with likely future extreme environmental events and to develop appropriate adaptation or mitigation strategies to minimise hazard and risk. A key goal is to ensure the physical resilience of the natural and man-made environment, and to establish more robustly the possible changes that may occur in river systems following any structural loss. In such work, models are becoming important tools aiding decision-making processes. However, these models need to be informed by a conceptual and quantitative understanding of the system being investigated. This inevitably leads to considerable, if not potentially unmanageable complexity, and challenges can arise when compiling a diverse range of inputs and parameters.

The pilot project brings together diverse factors from a wide range of disciplines, thus providing for a more holistic way of assessing the resilience of an aging engineered structure and the surrounding natural environment. The ambition is to express the combined factors in the decision-making process in a robust way which will lead to more informed strategies for dealing with future extreme events. The pilot project uses Clerkington Weir (a ‘run-of-river’ dam) on the River Tyne in East Lothian as a case study. Key benefits of the site include the relatively simple geomorphological (natural physical environment) setting, good access to the weir and surrounding area, and positive engagement from the landowner.

This report discusses the geomorphological component of the collaborative work, based on a desk and field survey. Geomorphological studies of run-of-river dams are few, and consequently considerable uncertainty exists regarding potential morphological and sedimentological effects of weir loss or removal (Csiki and Rhoads, 2010). Here, the geomorphological context of Clerkington Weir is described and an initial assessment is made concerning the influence that the weir currently has on the behaviour of the river. The report then considers conceptually how the river system might evolve if the Clerkington weir was lost or removed.

2 The Site

Clerkington Weir is located on the River Tyne in East Lothian, south-east Scotland, approximately 1.5 km to the south-west of Haddington. It is one of a total of 12 engineered barriers on the river (SEPA, 2018). The weir was originally built to provide water power for a former grain mill on Clerkington Estate, delivered by a mill lade. The age of the weir is not precisely known. It is shown on historical Ordnance Survey maps from 1855, but not on the earlier Roy Military Maps of Scotland from 1752-55.

2.1 RIVER TYNE CATCHMENT

The River Tyne has a total drainage area of 318.27 km^2 (Figure 1). It is sourced in the Moorfoot and Lammermuir Hills and flows in a general north-eastward direction to enter the outer Firth of Forth at Tynemouth. The stream network for the Tyne catchment is shown in Figure 1b. This network was extracted using ArcGIS hydrology tools and an assumed 0.1 square km area for stream initiation, which matches reasonably well with water courses shown on Ordnance Survey maps. The main stem of the River Tyne can be described as a 6th order stream, using the terminology of Strathler (1952). Clerkington Weir [NGR 350610 672345] is located approximately one third of the way down the main stem, at an elevation of 48 m above Ordnance Datum (O.D.) (Fig. 2A). The weir lies approximately 400 m downriver from the confluence of the 5th order Coulston Water [NGR 350490 672000]; the subcatchment above Coulston Water increases the contributing drainage area by some 70 km^2. At the Clerkington Weir, the river drains a total area of approximately 250 km^2, representing some 79% of the entire Tyne catchment (Fig. 2B).

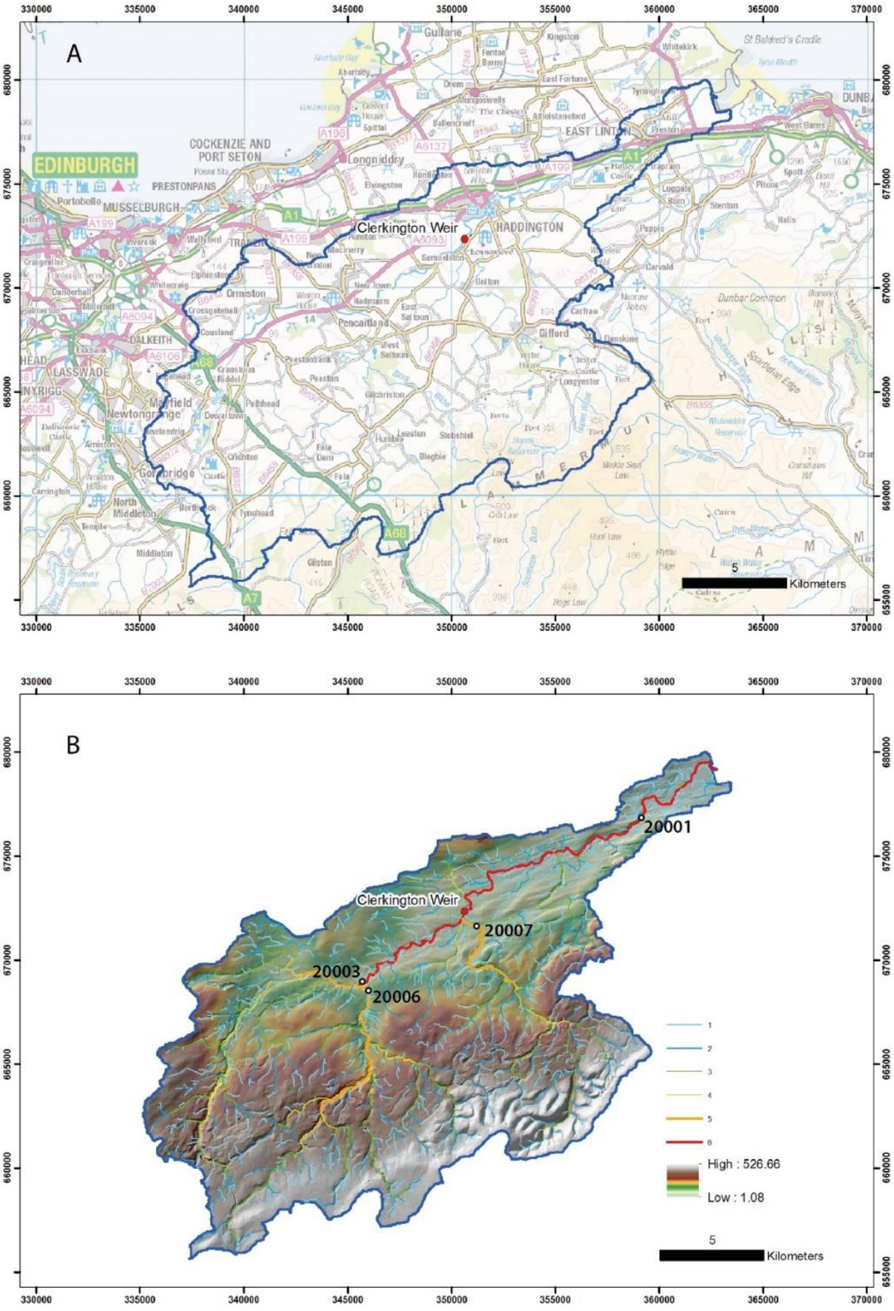
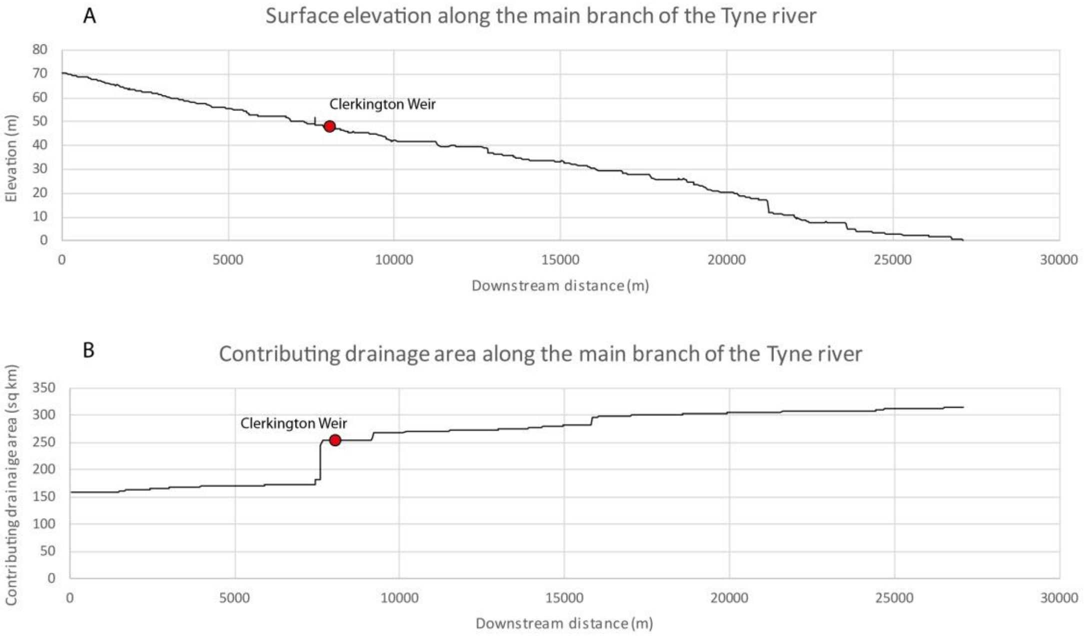


Figure 1. A. Location of the Tyne catchment in south-east Scotland. B. Catchment relief and stream network. Hill-shaded and coloured relief model based on UK Perspectives elevation data © UKP/Getmapping Licence No. UKP2006/01. Numbers refer to gauging stations: 20007 = Coulston Water at Lennoxlove, 20006 = Birns Water at Saltoun Hall, 20003 = Tyne at Spilmersford, 20001 = Tyne at East Linton.

The National River Flow Archive (National River Flow Archive, 2018) contains river flow data from 4 gauging stations within the Tyne catchment: the Tyne at East Linton (no. 20001); the Coulston Water at Lennoxlove (no. 20007); the Tyne at Spilmersford (no. 20003); and the Birns Water at Saltoun Hall (no. 20005). In addition there is a further station on the adjacent Beil Water (no. 20006), which has a similar catchment hypsometry and drains into the Belhaven Bay, approximately 2.5 km to the south-east of Tynemouth. Using mean flow values from these stations, an area-discharge relationship can be derived for the catchment (Fig. 3A). Also shown in Figure 3B is a relationship derived using maximum peak flow values from the water year 2000-2001 – during which there was one of the largest recent flood events on the Tyne (note that, with the exception of the Coulston Water at Lennoxlove, flow values are extrapolated for the 2000-2001 maximum flow event). Using these relationships, the mean flow and the maximum 2000-2001 flow on the Tyne in the vicinity of Clerkington Weir are estimated to be about 2.2m^3s^{-1} and 114 m^3s^{-1}, respectively.



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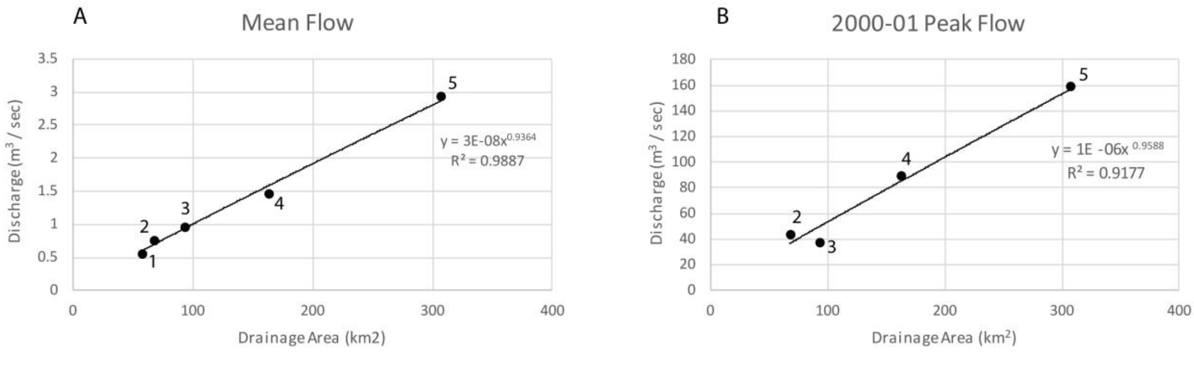

Figure 3. Drainage area-discharge relationships from gauging station data for (A) mean flow over the total station recording period and (B) maximum peak flow from the water year 2000-2001. 1 = Beil Water, 2 = Coulston Water at Lennoxlove, 3 = Birns Water at Saltoun Hall, 4 = Tyne at Spilmersford, 5 = Tyne at East Linton.

2.2 LOCAL SETTING

The geomorphology of a 0.23 km^2 area around Clerkington Weir (Fig. 4A, B) was assessed by desk study and from field survey. The river flows for a distance of 970 m across the study area, and drops in elevation by approximately 2.5 m, with an overall average gradient of 0.0025 m/m. Throughout the site, the river is best described as a plain bed and active single thread system, following the terminology of Kitchen (2016).

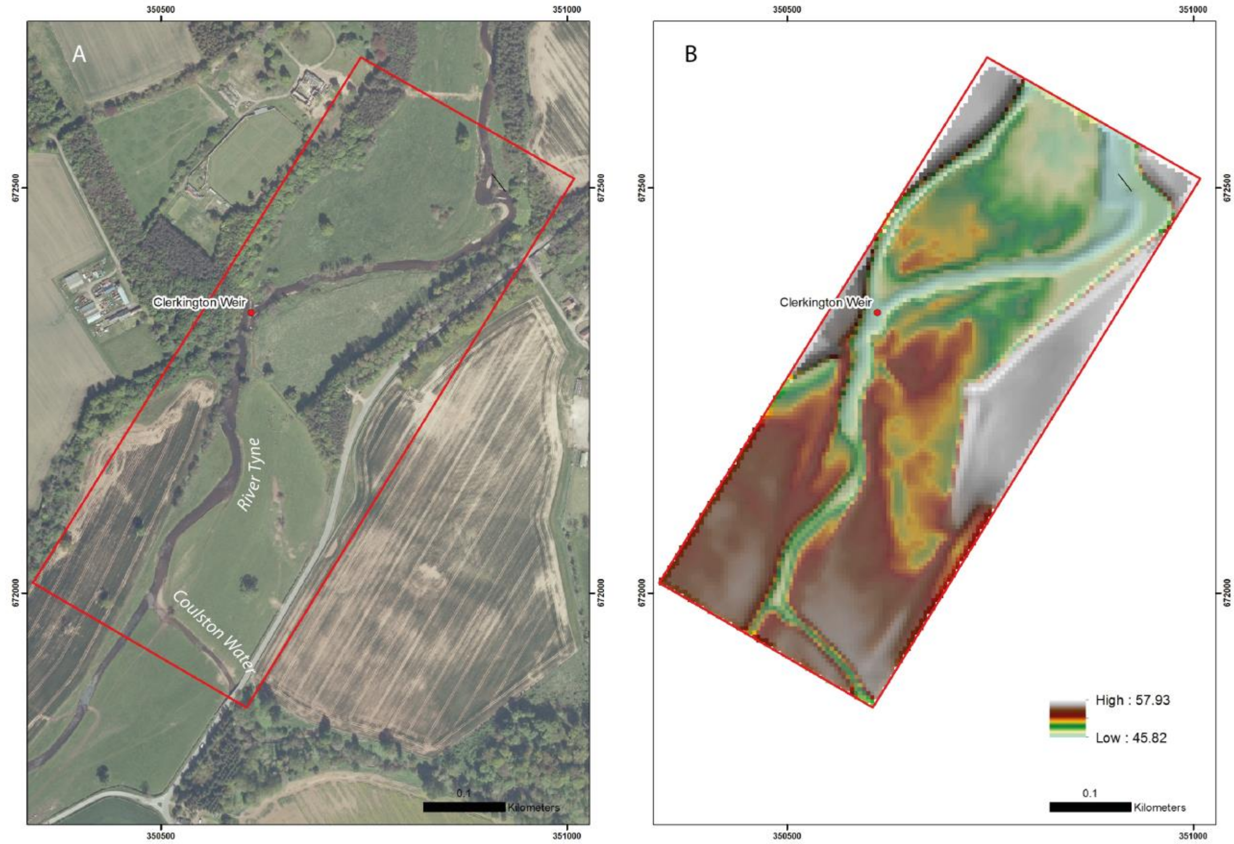

Figure 4. A. Aerial photograph (2009) of the study site around Clerkington Weir. RGB Aerial Photography © GeoPerspectives. B. Hill-shaded and coloured relief model of the study site, based on UK Perspectives elevation data © UKP/Getmapping Licence No. UKP2006/01.

Downstream from the Coulston Water confluence, the River Tyne occupies a 150-250 m wide floodplain, bounded to the north-west and to the south-east by slopes underlain by glacial till (BGS, 1978)(Fig. 5). Small river terraces and abandoned channels are present on the flood plain surface, providing evidence for past channel migration (see below). Deposits of alluvium have been laid down by the river across the flood plain. The nature of these alluvial deposits at the site is shown in two section logs from exposures in river banks (Fig. 6).

Section 1 is from the southern river bank, approximately 10 m downstream from the weir. The sandy loam topsoil overlies a loose- to medium-dense fine silty sand, which in turn overlies a soft to firm sandy clay. In the clay, at approximately 0.6 m depth below the ground surface, fragments of barbed wire were observed, indicating relatively recent localised reworking of these near-surface sediments. A Torvane strength of 15 kPa (n = 20) was measured in the sandy clay unit. Below the sandy clay, 2-5 cm thick layers of firm sandy clay alternate with fine to medium sand. The river level was approximately 0.5 m below the lowest exposed part of this unit, but the remaining material was obscured by vegetation.

Section 2 is from the north bank of the river approximately 200 m downstream from Clerkington Weir. At this section the sandy loam topsoil overlies approximately 0.6 m of dry, slightly cemented/hard fine sandy silt. The silt rests on a 0.4 m thick unit of medium-dense sand, which overlies a sandy gravel which continues down to the base of the section at the river bed.

In addition to these two sections, sediments were examined close to the water level at the northern bank of the impounded reach, a few metres upstream from the weir. These sediments comprised soft sandy silty clay from the water level to 1 metre above the water line. A Torvane strength of 11 kPa (n=20) was measured for these sediments. Below the water level, the sandy clay is very soft. Locally, sections the river banks have been artificially reinforced by boulders and concrete slabs, as shown in Figure 5.

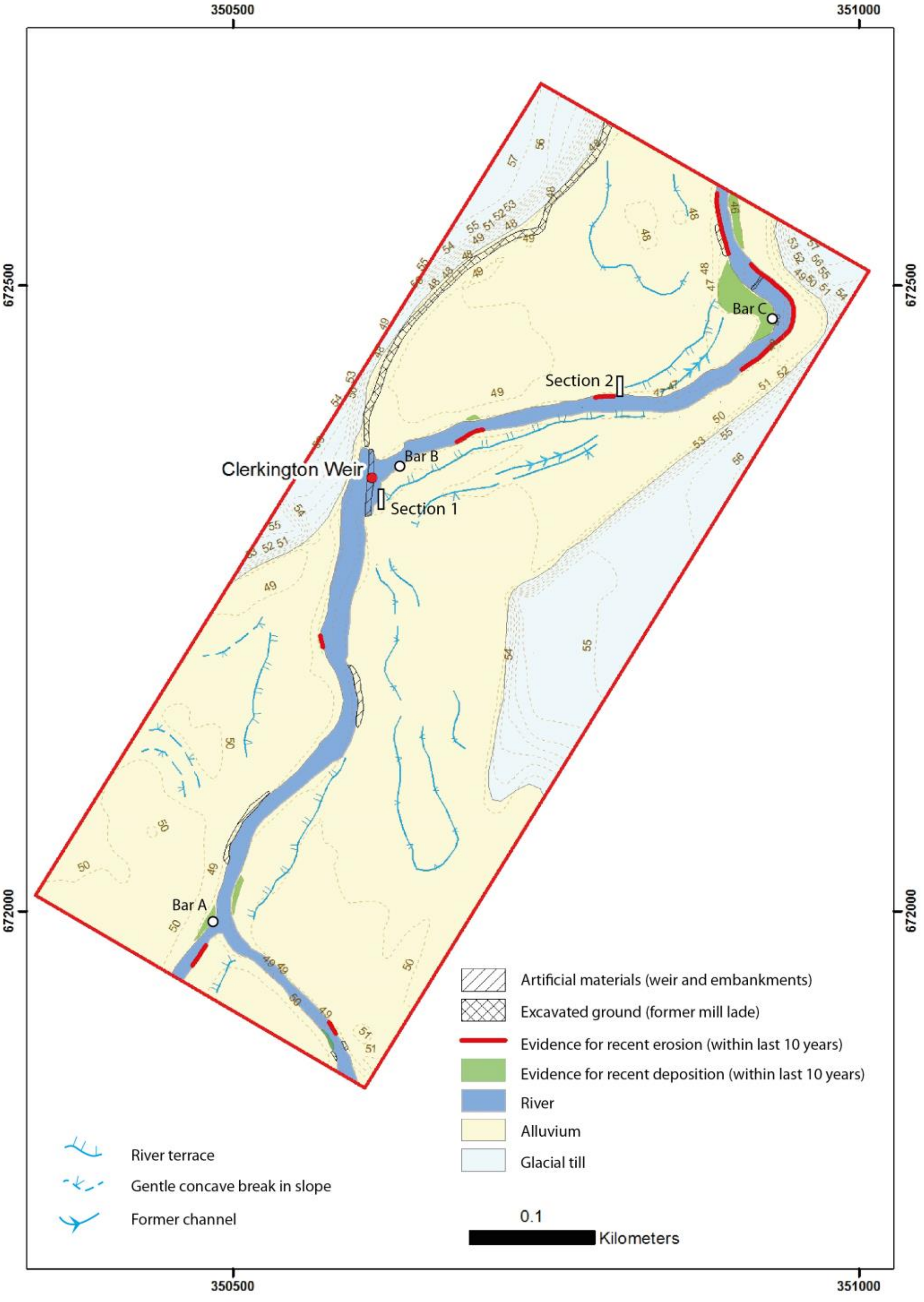

Figure 5. Shallow geological and geomorphological map of the survey area, based on field survey.

The river bed materials are predominantly gravel; clast sizes were measured at three gravel bars within the study area (Figs. 5,7). Median clast sizes at bars A and B were 35 and 45 mm respectively, while at bar C, the median clast size was just 15 mm. Possible reasons for the differences in clast size are discussed further below. Also of note is that for a distance of approximately 300 m upstream from the weir, the gravel bed was covered by a very thin drape of silt.

There are no surface exposures of bedrock within the site or its immediate vicinity. Published geological maps indicate that the bedrock under the site belongs to the Aberlady Formation of Carboniferous age. This formation generally consists of sandstones, siltstones and mudstones, with some layers of seatrock. The BGS borehole database does not contain any records of boreholes drilled within the vicinity of the weir, and the depth to bedrock (rock head) at the site is not known. Based on knowledge from other sites in similar settings a rock head depth of 2-10 m below the ground surface may be considered an appropriate estimate.

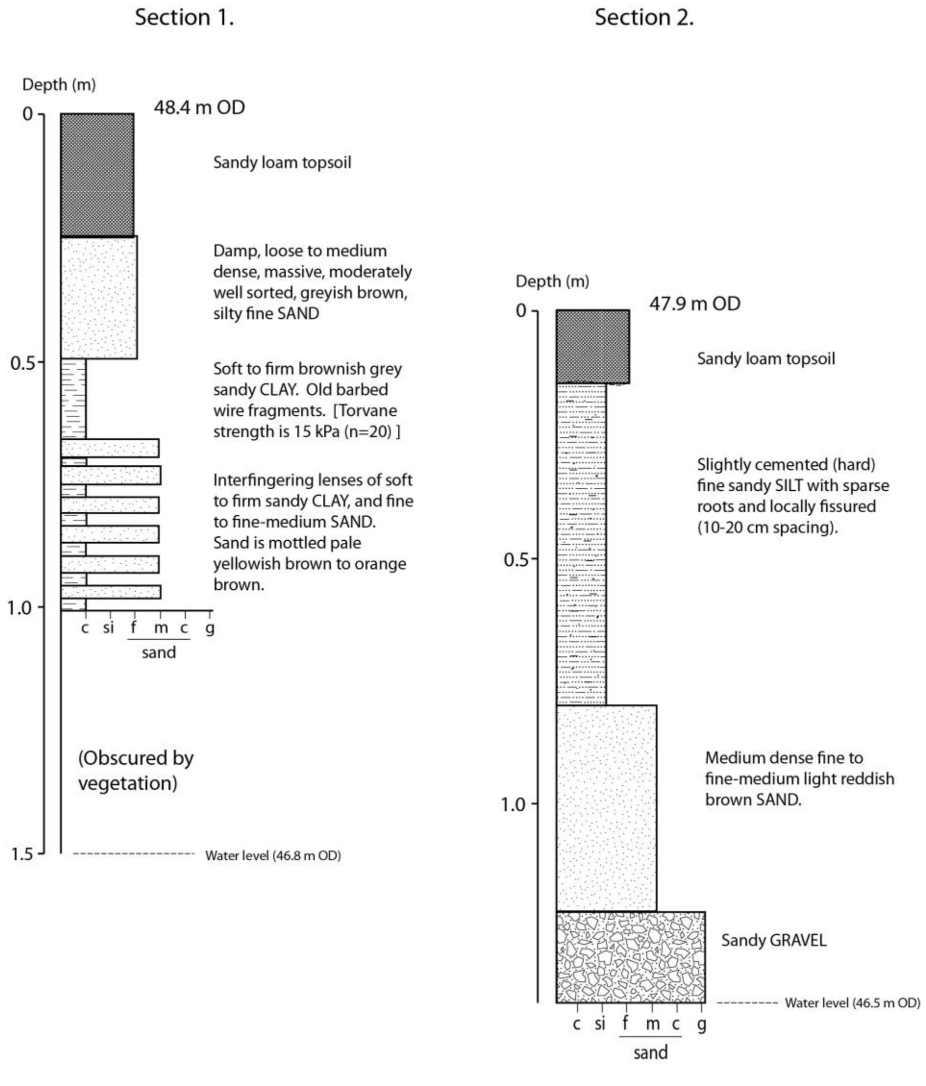

Figure 6. Sediment logs from 2 exposures along the riverbanks. Locations are shown in Fig. 5.

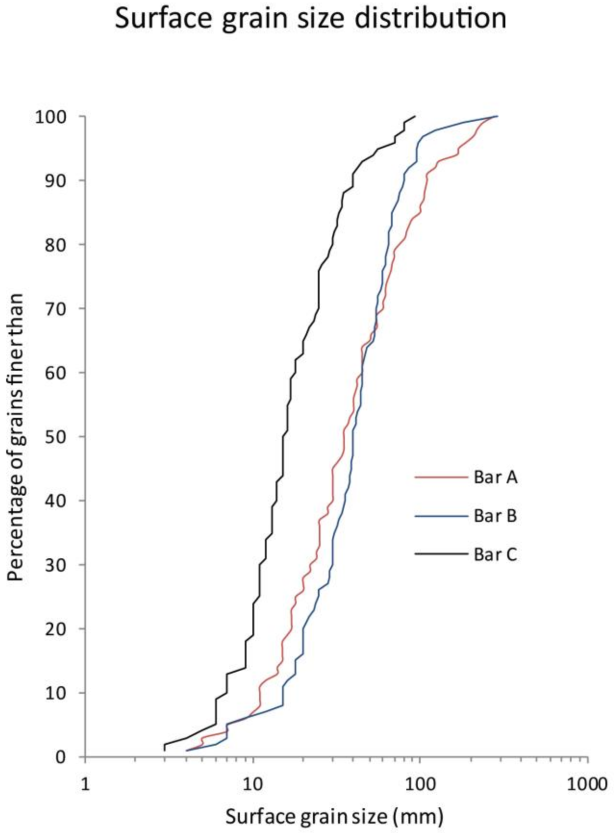

Figure 7. Size distribution of grains on the gravel river bed taken from three bars, based on measurements of 100 clasts at each site. The locations of the bars are shown on Fig. 5.

3 Historical River Change

Changes in the course of the river Tyne through the site have been identified through comparison in a Geographical Information System (GIS) system of: (i) historical Ordnance Survey maps (surveyed in 1855 and 1895); (ii) aerial photographs dating from 1946, 1988 and 2009; and (iii) a GPS survey of the river centreline undertaken in September 2018 (see below). An overview of these changes is presented in Figure 8.

Over the past 150 years, most stretches of the river have migrated to some extent across parts of the flood plain. However, the river has clearly been 'pinned' at Clerkington Weir, since some time after the 1750s. The loci of the reaches immediately upstream and downstream of the weir over some 200-300 m also appear to have remained relatively static over this period. Prior to the installation of the weir, it appears that the river was more sinuous upstream and downstream of the weir, as indicated by the river's course on the Roy Military Survey of Scotland (1752-55) (National Library of Scotland online map viewer; https://maps.nls.uk/military/). Although it is difficult to locate precisely the features shown on the Roy map in relation to the present day geomorphology, the river is shown to be more sinuous at that time, before the weir's construction. In particular, two clear meander loops immediately downstream from the Gifford Water confluence are evident; the second of these appears close to the location that weir now occupies.

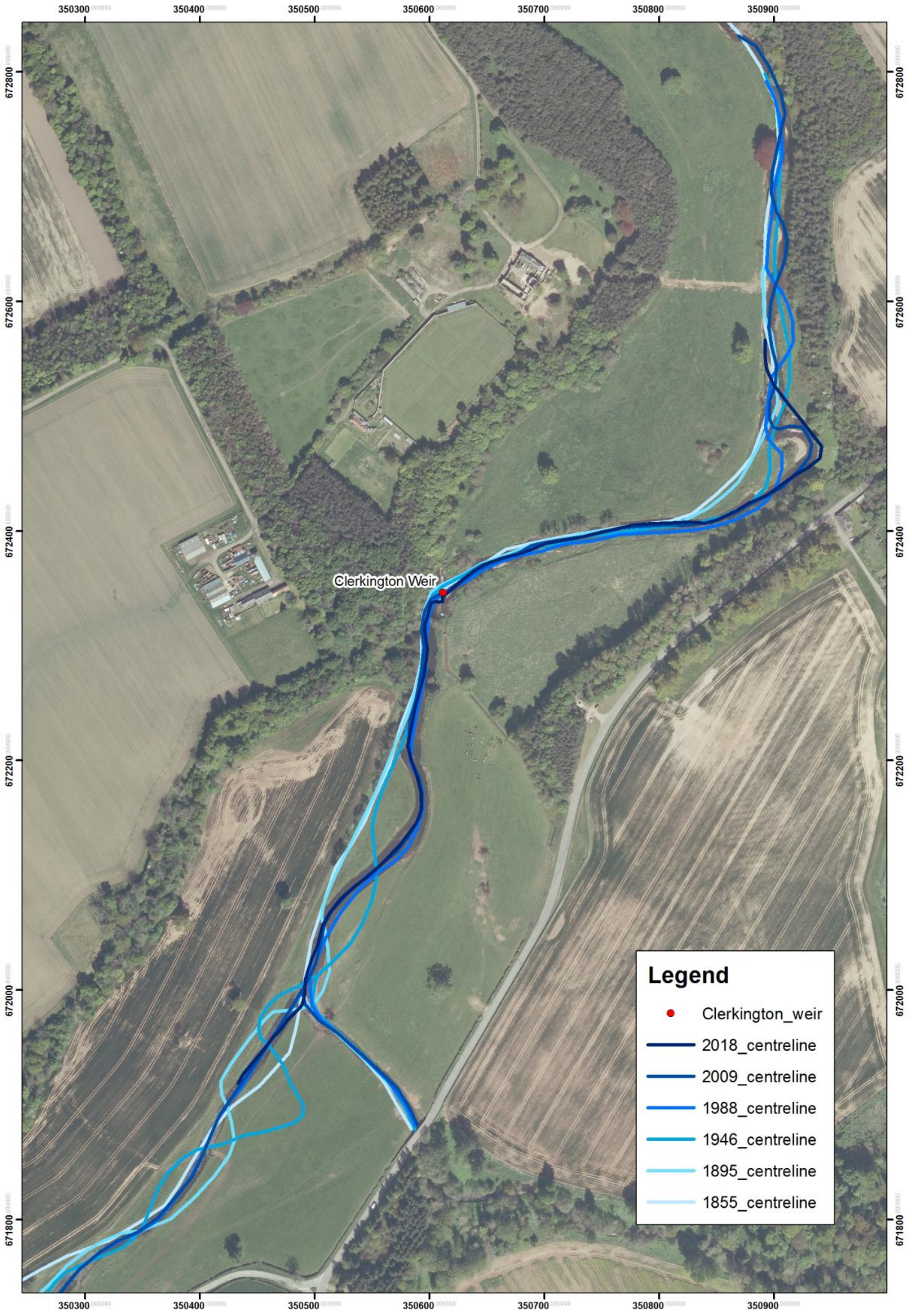

Figure 8. Changing channel centreline positions from the period 1855-2018, derived from historical Ordnance Survey maps, dated aerial photographs, and a recent GPS survey. RGB Aerial Photography © GeoPerspectives.

4 GPS Survey

A GPS survey was undertaken on the 28th of September 2018, using a Leica GS08 GPS system to map the position of the river banks, and determine the river bed centre line long profile. The river bed elevation was measured down the river centre line with an average interval spacing of 12.5 m. The river bank positions and water surface elevations were also measured at similar intervals.

The river bank positions are shown on the map in Figure 5. The areas in red and green indicate where the 2018 river bank position differs from that shown on the most recent aerial photograph held by BGS (2009). These are interpreted as zones of recent bank erosion and deposition. Of note is the large area of deposition at the north-eastern corner of the site, where the river is continuing to erode the outside bend and deposit a gravel bar on the inside bend. This recent river migration has revealed a second smaller weir within the study area (Fig. 9). This lower weir had previously been buried by alluvial sediments and is now once more uncovered as a result of repeated migration of the river.

Figure 9. The lower weir (approximately 400 m downstream from Clerkington Weir), which was previously covered by alluvium, and has once more become exposed by channel migration.

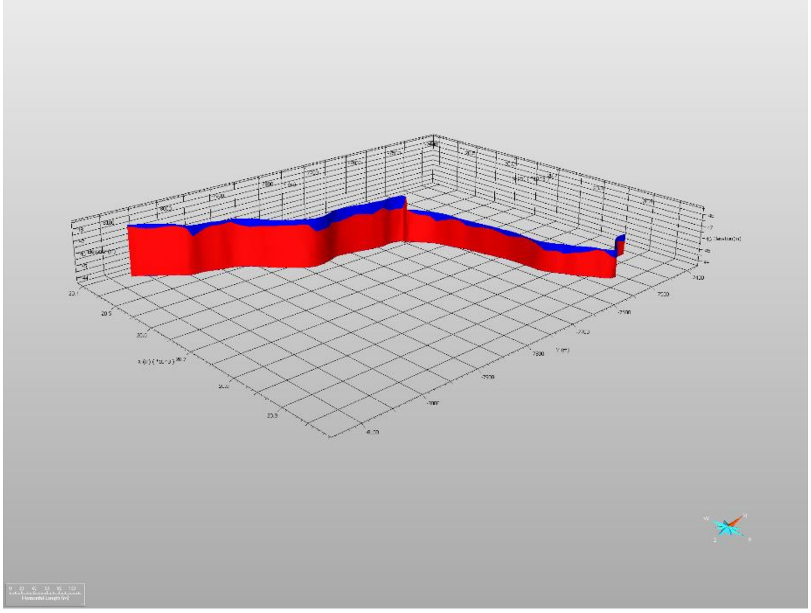

Figure 10. Plot of river bed (red) and water surface (blue) elevations from GPS data.

A plot of river bed and surface water elevation is shown in Figures 10 and 11. The riverbed profile suggests a pool-and-riffle river bed morphology. Water depth clearly increases for a distance of approximately 300 m on the upstream side of Clerkington Weir (Fig. 11). An increase in depth over a distance of approximately 50 m is also apparent on the upstream side of the newly exposed lower weir. For the Clerkington Weir, the increase in water depth also coincides with a more gradual increase in river width from 10 m to 50 m on the upriver reach (Fig. 12).

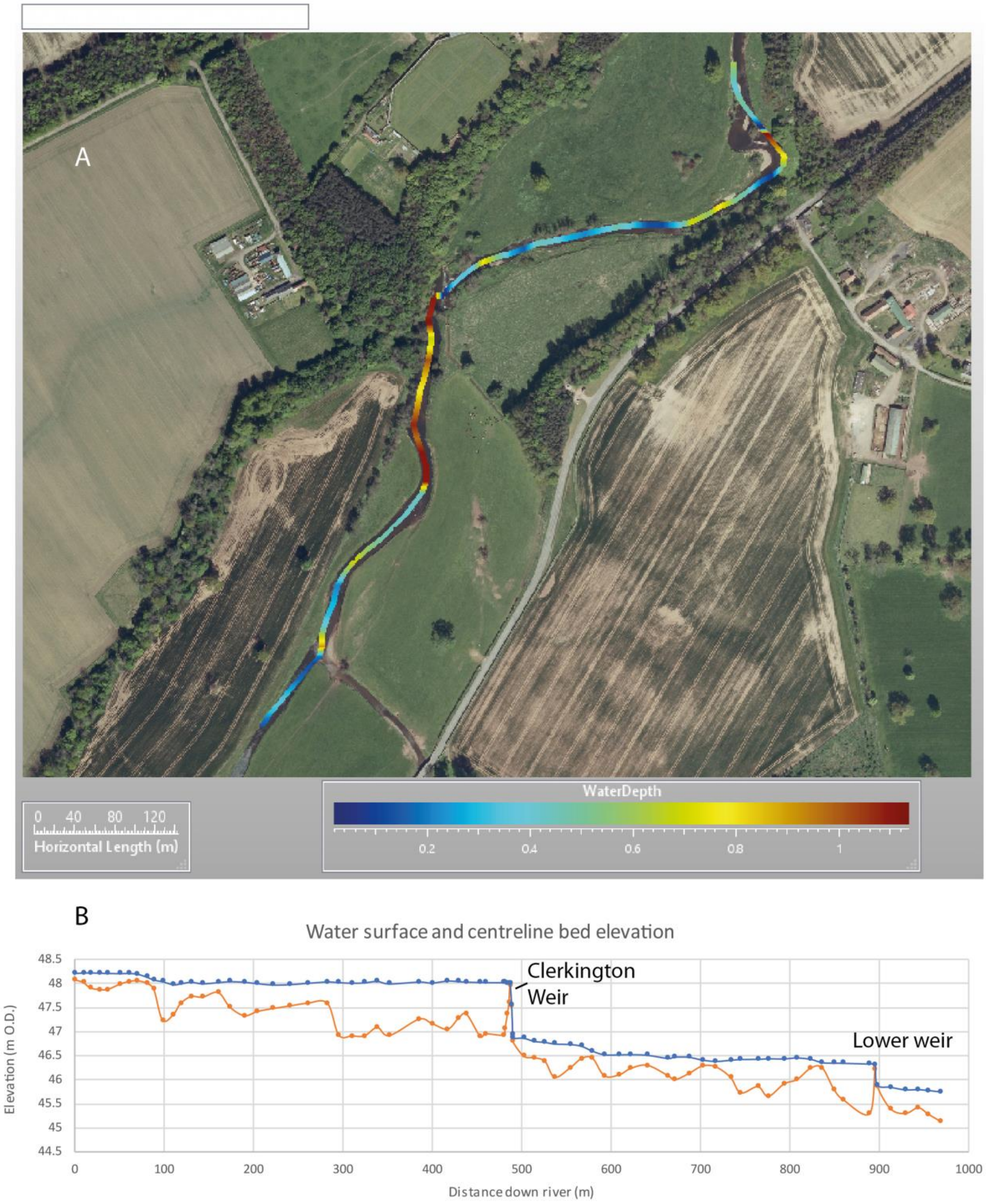

Figure 11. A. Plot of water depth along the surveyed profile. RGB Aerial Photography © GeoPerspectives. B. Graph showing water surface elevations and river bed elevations along the survey profile.

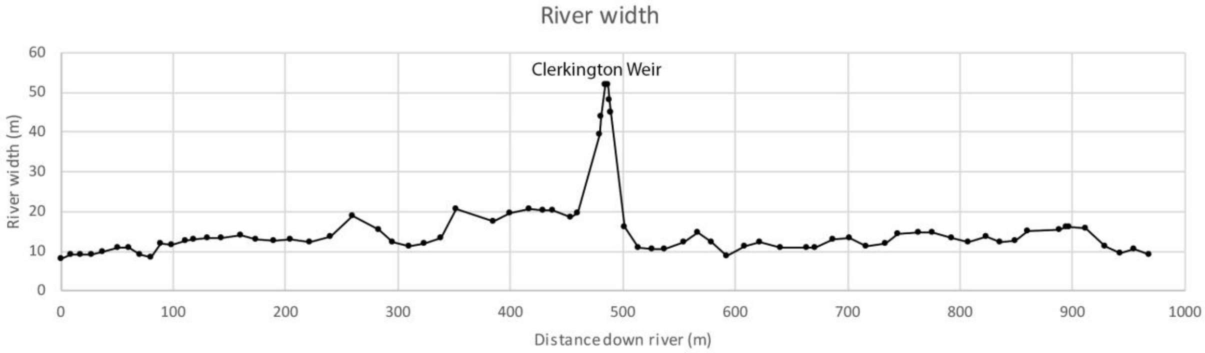

Figure 12. Graph showing river width along the surveyed profile.

5 Derived river characteristics in the vicinity of Clerkington Weir using the 28th September 2018 GPS data.

The GPS data were used to derive basic estimates of flow (e.g. shear stress, mean velocity) based on simplified channel geometry. These estimates can then be used as an initial approach for evaluating the influence of the weir on the river (see below).

A linear trend for the water surface slope was determined using the GPS data points across five characteristic reaches. There is some uncertainty in determining the water surface slope, particularly over the second reach (98-486 m) where the overall fall in elevation is close to the vertical precision of the GPS (~0.02 m). The resulting trends in the slope of the water surface slope for each of the reaches are given in Table 1.

Table 1. Slope trends along surveyed reaches of the river Tyne

Distance	Description	Slope	R^2
0 – 98 m	Upriver of Gifford Water confluence	y = 0.0016x	0.66
98 – 486 m	Gifford confluence to upstream side of Clerkington Weir	y = 0.00002x	0.04
490 – 718 m	Straight narrow channel downriver from Clerkington Weir	y = 0.0022x	0.93
718 – 894 m	River bend to proximal side of lower weir	Y = 0.0005x	0.55
900 – 970 m	Downriver from lower weir	Y = 0.0019x	0.89

The slope of the water surface upstream from the weir has the form of an M1 backwater curve (Chow, 1959). It should be noted that slope values will vary over time with changing river stage and water height relative to the weir top. Using the slope values derived from the GPS survey on the 28th September 2018, values for bed shear stress (τ_b) were calculated along the centreline profile using

$$\tau_b = \rho g h S$$

where ρ is the density of water (1000 kgm^{-3}), g is gravitational acceleration (9.81 ms^{-2}), h is the water depth and S is the water surface slope. The bed shear stress values are plotted in Figure 13.

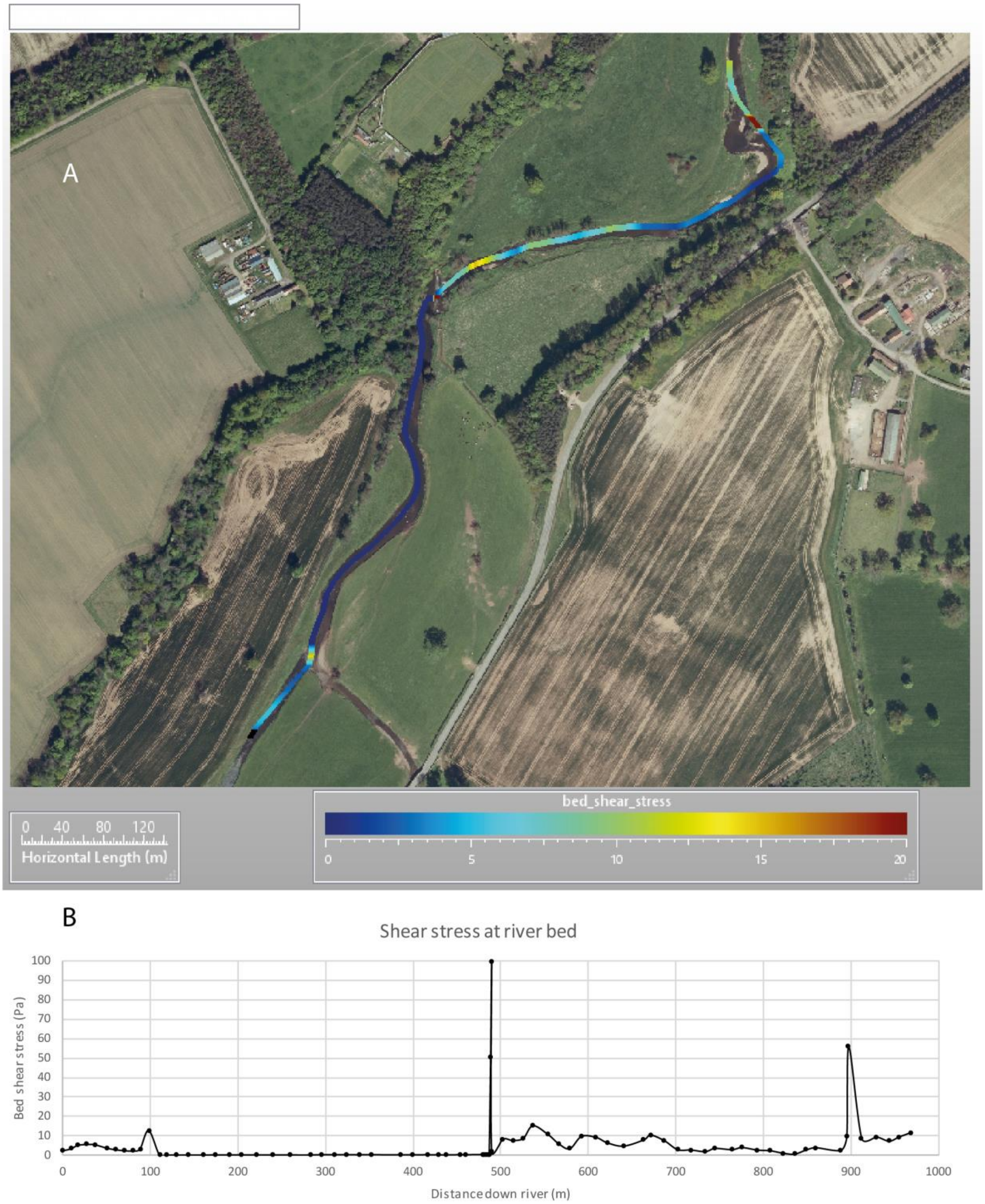

Figure 13. A. Plot of calculated basal shear stress along the surveyed profile. RGB Aerial Photography © GeoPerspectives. B. Graph showing basal shear stress values along the same profile.

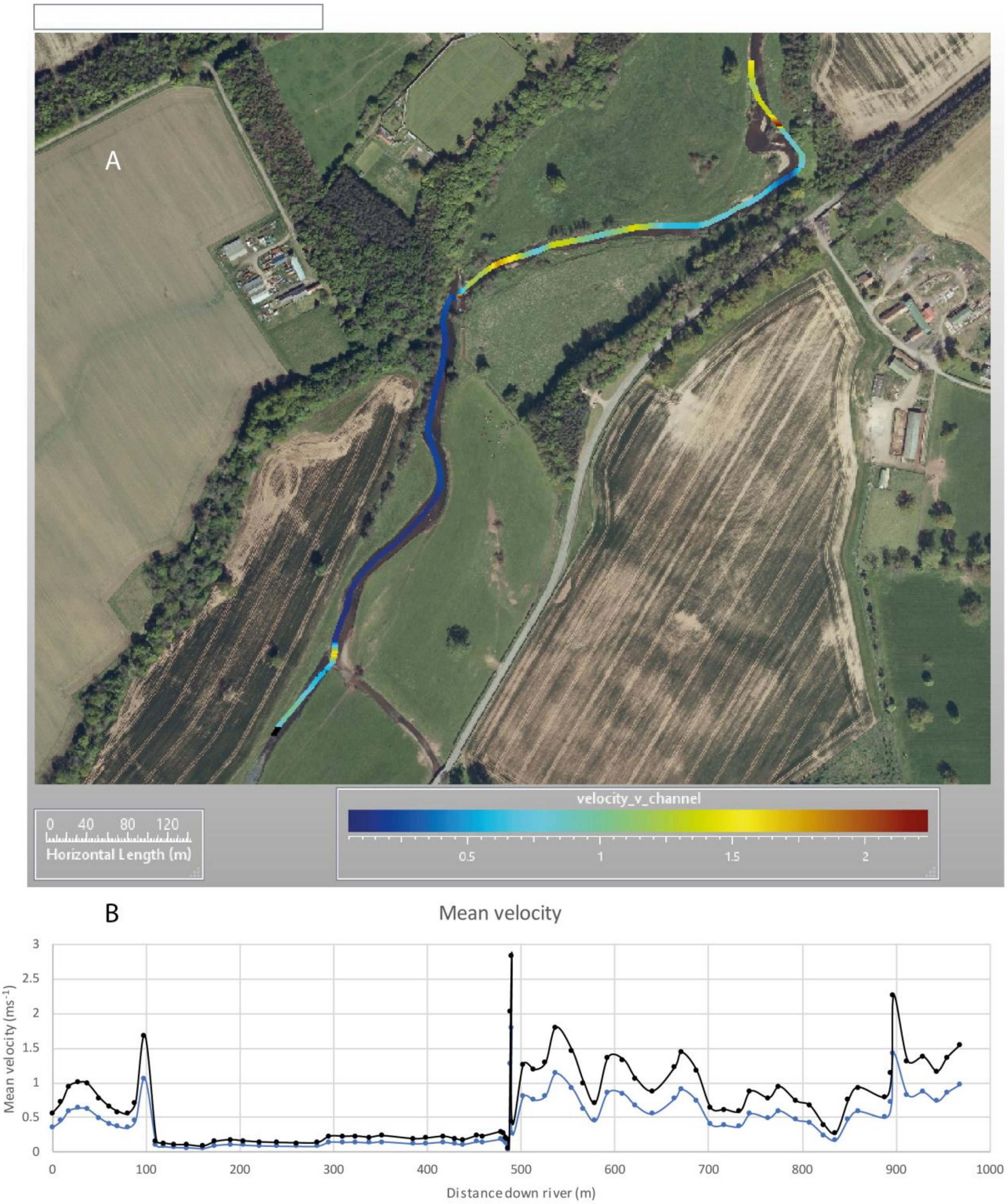

Figure 14. A. Plot of calculated mean velocity along the survey profile. RGB Aerial Photography © GeoPerspectives. B. Graph of calculated mean velocity for an assumed rectangular channel (black line) and 'v-shaped' channel (blue line).

Calculated mean velocity (U_a) is shown in Figure 14, and was derived using Manning's equation

$$U_a = \frac{S^{\frac{1}{2}} R_h^{\frac{2}{3}}}{n}$$

where *R* is the hydraulic radius (the cross-sectional area of flow divided by the wetted perimeter) and *n* is the Manning's roughness coefficient, taken here to be 0.03 based on the site context and the river bed material (*cf.* Chow, 1959). Two estimates of mean velocity are shown in Figure 14B, based on simplified representations of the channel cross-section shape – either a rectangle (black line) or a triangle (blue line).

Using these velocity values, discharge (Q(m^{3}s^{-1})) was calculated along the study profile (Figure 15). The scatter in the calculated values reflects, amongst other factors, uncertainty about the true cross-sectional channel geometry and how it varies down the profile, uncertainty of local water surface slope values, and assumptions in the use of a constant roughness coefficient, n, down the profile. There may also be losses and gains of water through processes such as groundwater-river interaction and seepage through the weir, which may impact on Q; these may be small but are unknown. Despite the uncertainties, the average discharge value for the ‘triangle-shaped channel’, calculated using the above approach over the whole 970 m long profile (2.06 m^{3}s^{-1}) agrees reasonably closely with the mean discharge value at the site that was extrapolated from the gauge station area-discharge relationship (2.225 m^{3}s^{-1}).

Stream power (γ(Wm^{-1})) is plotted in Figure 16 and was calculated from:

$$\gamma = \rho g Q S$$

using both sets of estimated values for Q. Figure 16 also shows the stream power that might be expected under a more evenly-graded river, given a constant surface slope along the 970 m profile (green line).

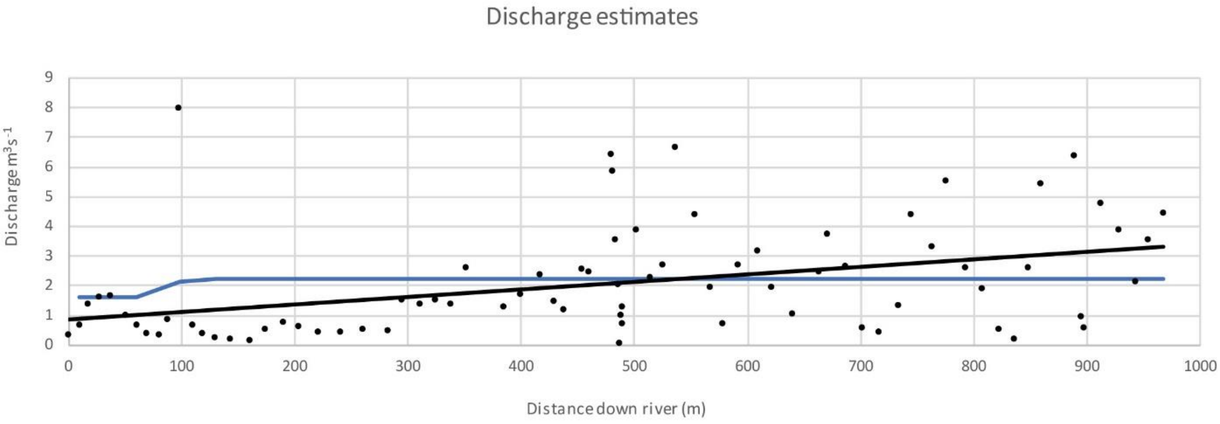

Figure 15. Graph showing different calculations for discharge through the survey area. Black dots show the scatter in calculated discharge at the long profile survey points (described in text) highlighting, amongst other factors, uncertainty in knowledge about channel cross sectional geometry. The black line shows the trend of these values. The blue line shows the discharge values calculated from the mean flow area-discharge relationship derived from catchment gauging station data.

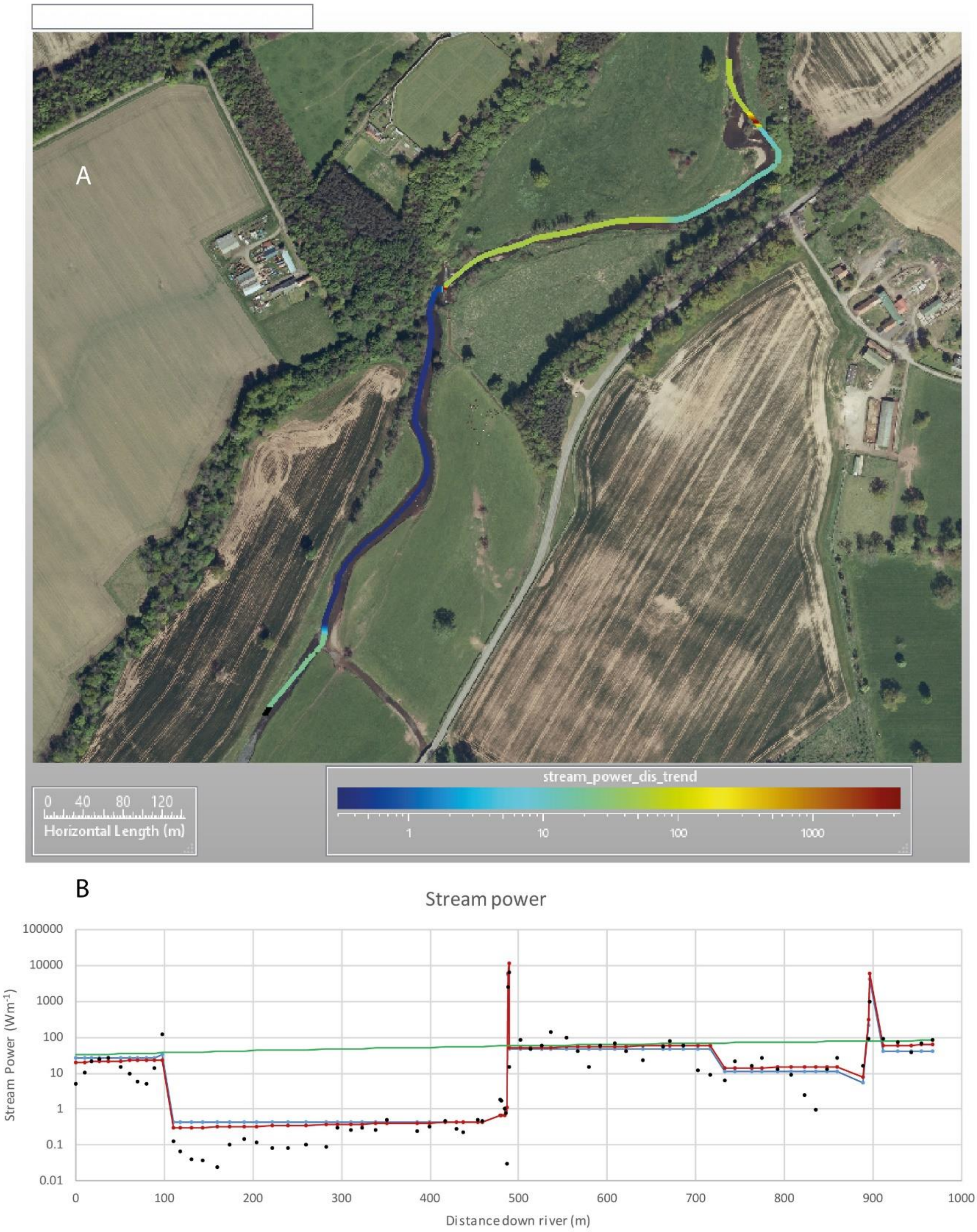

Figure 16. A. Plot of stream power along the survey profile. RGB Aerial Photography © GeoPerspectives. B. Graph showing stream power calculations obtained using different approaches. The dots show values derived from the long profile survey. The red line is derived using the discharge trend obtained from the survey points. The blue line is derived using the drainage area-discharge relationship. The green line represents stream power values that might be expected under a more evenly graded river if the surface slope was constant along 970 m-long profile.

6 Discussion

6.1 INFLUENCE OF THE WEIR ON THE RIVER

In a discussion of the effects that weirs can have on river geomorphology, Kitchen *et al.,* (2016) include:

- Increased water levels, depths, and flow widths upriver from the weir
- Causing an upriver impoundment zone of low-energy flow conditions
- Interruption of sediment transport
- Reduced flow velocities upriver from the weir
- Modification to floodplain wetting frequency

Both the river depth and river width increase from approximately 300 m upstream of the weir (Fig 11A, 12). These are associated with a reduced water surface slope and a reduction in the calculated average flow velocities over a distance of 400 m upriver from the weir (Fig. 14). These effects are also evident in the stream power and basal shear stress estimations, which highlight the limited ability of the river to do geomorphic work upriver from the weir (Figs. 13, 16).

These effects of this are clearly evident at Clerkington Weir, where sediment transport appears to have been interrupted in two ways. First, during the moderate to low flow conditions that existed at the time of survey, a silt drape was observed overlying the more natural river bed gravels over the distance of reduced bed stress that exists upstream from the weir. Second, the centreline bed profile data suggests that a ‘plug’ of gravel (located approximately 200-400 m upstream of the weir) has become deposited at the upstream end of the zone of lower shear stress (Fig. 11B, 100-300 m distance). Having been transported largely from upstream sources during higher flows, the gravel has become trapped at the boundary of the lower energy zone, where the impoundment of water by the weir takes effect. This kind of ‘plug’ or ‘wave’ of gravel located at some distance upstream from a weir has been described in a similar setting on the River Monnow in Wales (Thomas *et al.,* 2015).

For a distance of approximately 200 m downstream from the weir, bed shear stress, average flow velocity and stream power values all increase. Immediately downstream of the weir, the river has been starved of coarser sediment, and has eroded material to re-establish a sediment load that matches the transport capacity (Csiki and Rhoads, 2010). The fixed orientation of the weir means that the channel is effectively straight immediately downstream of the weir. This effect, coupled with enhanced scour from plunging turbulent flows over the weir face, has led to increased incision. As a result, the channel bed now rests relatively lower below the floodplain surface, reducing the wetting frequency of the floodplain downstream from the weir. The enhanced incision, coupled with the cohesive nature of the river banks (Fig. 6), has, for the moment, effectively ‘fixed’ the channel in this downstream reach.

The conditions generated by the weir may be able to explain the relatively static spatial position of the river in the immediate upstream and downstream reaches, in comparison to reaches farther up and down stream (Fig. 8). This stabilising geomorpholgical influence of weirs has also been suggested by modelling studies in the Derwent Valley Mills world heritage site, where the weirs appear to play an important role in reducing river channel dynamics (Howard *et al.,* 2017).

6.2 LIKELY EVOLUTION FOLLOWING WEIR LOSS

Were the weir to be lost or removed, increases in water surface gradient, flow velocity and shear stress (and stream power) would be expected upstream of the former structure. This would result in sediment entrainment and transport (Csiki and Rhoads, 2010). Initially, erosion of the bed would occur in the vicinity of the former structure. However, this would be likely to continue upstream for distances of at least 400 m (the length of the current low energy flow zone). These kind of effects have been produced in modelling studies. For example, in a study by Howard *et al.,* (2017), model simulations produced incision upstream from weirs for distances up to one km. Incision of channels and water lowering can be associated with bank instability and concomitant channel widening, and is influenced by the material properties of the bed and bank sediment (Pizzuto, 2002; Wildman and MacBroom, 2005).

The gravel ‘plug’ that appears to have accumulated upstream from the weir may play an important role influencing the response. Following weir removal, a gravel wave on the river Monnow acted to divert erosion towards more easily entrained material at the river banks, causing 6-7 m of bank widening on the former impounded reach (Thomas *et al.,* 2015). Similar effects could potentially occur upstream from Clerkington weir, particularly considering the very soft, fine grained material observed at some of the banks and the lack of stabilising vegetation around the impounded reach. The evolution of any sediment wave would be important; current studies suggest that these features undergo slow dispersal down river (Lisle *et al.,* 2001; Thomas *et al.,* 2015). The sections of river bank that are reinforced by boulders and concrete slabs would also influence the dynamics of any channel adjustment as the river grades to non-weir conditions.

Below the weir, deposition would be expected as river bed rises to meet decreasing upstream elevation (Csiki and Rhoads, 2010; Howard *et al.,* 2017). A potential impact of increasing sediment supply and locally raising bed would be increasing water surface level in the downstream reach, which could increase the likelihood of channel adjustments. Weir removal on the river Monnow has resulted in an increase in sinuosity – particularly where banks are not reinforced by vegetation (Thomas *et al.,* 2015). Under natural conditions, a similar increase in sinuosity may be expected to occur at the Clerkington Weir, as suggested by the depiction of meanders in Military Survey maps which capture the pre-weir river in naturally graded conditions.

Figure 16 B shows stream power values that might be expected along the surveyed section of the river Tyne, if the river became more evenly graded with a more constant water surface slope (i.e. with no weirs). The reach upstream of the Coulston Water confluence and the reach below Clerkington Weir appear to most closely match those ‘stream power conditions’. Perhaps these reaches offer an illustration as to the conditions that the river would evolve towards in a scenario where the weir is lost.

7 Recommendations for further work

This report has described the findings from an initial desk and field survey of the geomorphology of the River Tyne at Clerkington Weir. In order to more completely understand the influence of the weir on the river (addressing some of the uncertainties discussed in this report), and to more robustly establish possible changes that may occur following loss of the weir, further stages of geomorphological investigation would be recommended. One of the most important additional datasets to acquire would be a far more complete survey of the river bed topography. This could be achieved either by regularly-spaced cross-channel GPS surveys, or preferably, through the use of an autonomous surface vehicle (ASV) with a single or multibeam system to map the full river bed topography. The potential ‘gravel plug’ upstream from the weir would be an important focus for this. Ideally, surveys should be repeated over time to capture the river bed dynamics. Other work to consider would be surveying and geotechnical testing of the river bank and bed material in different areas, in order to understand which zones would be most likely to be affected by sediment entrainment and transport (possibly causing widening).

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

BGS. 1978. Haddington, Scotland Sheet 33 (W). Drift Edition. Institute of Geological Sciences. Edinburgh.

CHOW, V. T. 1959. Open-Channel Hydraulics. New York. McGraw-Hill.

CSIKI, S., RHOADS, B. L. 2010. Hydraulic and geomorphological effects of run-of-river dams. *Progress in Physical Geography*, 34(6), 755-780.

HOWARD, A. J., COULTHARD, T. J., KNIGHT, D. 2017. The potential impact of green agendas on historic river landscapes: Numerical modelling of multiple weir removal in the Derwent Valley Mills world heritage site, UK. *Geomorphology*, 293, 37-52.

KITCHEN, A., GAULDIE, R., PATTERSON, C., BENTLY, S., KIRKBY, A. M. 2016. River weirs: Design, maintenance, modification and removal. CIRIA C763, CIRIA, London, 295 pp.

NATIONAL RIVER FLOW ARCHIVE. 2018. *https://nrfa.ceh.ac.uk*, NERC CEH, Wallingford.

PIZZUTO, J. 2002. Effects of Dam Removal on River Form and Process. *Bioscience*, 52(8), 683-691.

SEPA (2018) Water Environment Hub. https://www.sepa.org.uk/data-visualisation/water-environment-hub/

STRATHER, A. N. 1952. Hypsometric (area-altitude) analysis of erosional topology. *Geological Society of America Bulletin*, 63 (11), 1117–1142.

THOMAS, R. J., CONSTANTINE, J. A., GOUGH, P., RUSSELL, B. 2015. Rapid channel widening following weir removal due to bed material wave dispersion on the River Monnow, Wales. *River Research and Applications*, 31, 1017-1027.

WILDMAN, L. A. S., MACBROOM, J. G. 2005. The evolution of gravel bed channels after dam removal: Case study of the Anaconda and Union City Dam removals. *Geomorphology*, 71, 245-262.