LONG-TERM CHANNEL RESPONSE TO A MAJOR FLOOD IN AN UPLAND GRAVEL-BED RIVER

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ABSTRACT

Long-term data quantifying the response of fluvial systems to geomorphically effective events are rare, limiting our ability to validate conceptual models of geomorphic evolution. Here we present geomorphic change data for a 200 m reach of the Thinhope Burn a small (12 km²) tributary to the South Tyne, Cumbria, UK, monitored since 2003. In July 2007 a severe flood resulted in a peak discharge of 60 m³ s⁻¹, and boundary shear stress maxima of 533 N m⁻², capable of mobilising metre-size boulders. The Thinhope Burn catchment showed ‘responsive’ behaviour to the event causing; full activation the valley floor and slopes, a peat slide in the headwaters, and delivery ~3077 m³ of gravel to the study reach. Ten years on, there appears to be limited evidence of recovery to the valley floor, possibly due to the effects of several wet winters. The channel and floodplain surface appear unconsolidated and vegetation-free, and as a consequence remains highly mobile during floods. Some climate change predictions for the UK uplands indicate wetter winters, that could push sensitive upland catchments closer towards ‘ tipping-point’, where thresholds are crossed within the fluvial system resulting in significant morphological changes to the river channel and it’s floodplain, and producing very high bedload transport volumes. A new regime of wetter winters may also halt recovery of upland rivers where the sediment system has already been fully activated by previous floods. We conclude that a better understanding of relative catchment sensitivity and the potential implications of climate-change induced increases in flows upon those catchments is needed to plan for the potential impacts of enhanced sediment loads upon flood risk.

Keywords: Flood risk, bedload transport, morphological change, sensitivity, thresholds

1 INTRODUCTION

By World standards, rivers in the uplands of the UK are usually considered to be ‘robust’ in character (Werritty and Leys, 2001), often exhibiting single-thread channels, flowing between stable vegetated and cohesive banks, transporting small amounts of bedload, and are regarded as supply limited (Newson, 1981; Milan et al., 2013). Occasionally however, upland streams can respond dramatically to extreme floods when thresholds are exceeded (sensu Schumm, 1979) within the fluvial system (e.g., Carling, 1986; Harvey, 1986; Warburton, 2010; Milan, 2012). In these situations slopes are often activated and supply sediments to slope channel-coupling zones, floodplains surfaces can be ripped apart and re-worked, and river channels can switch their pattern from single-thread to multi-thread (e.g. Harvey, 1986; Milan, 2012).

In the UK, the most classic documentation of channel change is for meandering channels, where Hooke (1995) used historical maps and aerial photographs to document meander migration and cut-off processes over decadal time frames for the Rivers Bollin and Dane in Cheshire. The advance of surveying technologies over the 1990s and 2000s (see Entwistle et al., 2018), allowed 3D assessment of morphological change; permitting DEMs to be produced from spatially distributed point data-sets. For the UK, notable studies include work on the wandering river Coquet in Northumberland (Fuller et al., 2003a,b) using total station survey, and the braided river Feshie; where Brasington et al. (2000) and Wheaton et al. (2010) used RTK dGNSS survey to create DEMs, to look at spatial patterns of erosion and deposition on an annual timescale. More recently, terrestrial laser scanning (TLS), aerial LiDAR (Milan et al., 2007; Lallias-Tacon et al., 2014; Milan et al., 2018), and SFM photogrammetry (Westoby et al., 2012; Schwendel and Milan, in press), have allowed better quantification of sediment budgets over time, however their use to help geomorphologists improve understanding of geomorphic work over time (Wolman and Gerson, 1978), has seen little attention largely due to the limited temporal scale of the investigation (typically less than 5 years).

There is renewed interest in river management of upland UK, particularly with respect to the implementation of natural flood management approaches, to address potential increases in flood magnitudes as a result of global climate change (Lane, 2017). In particular, little is known about the responsiveness of the fluvial sediment system to increased flood magnitudes, and the effects on sediment transfer; which could have implications for flood management further downstream in lowland areas. There has been limited work quantifying how rivers...
respond to extreme events, and even less on the morphological processes of recovery at an annual temporal resolution. This study continues one of the few investigations to attempt to quantify this from a geomorphological perspective (Milan, 2012), providing information on two-dimensional channel changes in the decade since a threshold exceedence event in an upland gravel-bed stream.

2 STUDY SITE

This investigation focused on a 200 m reach of the Thinhope Burn, a small 12 km² tributary to the River South Tyne situated in the north Pennines in Cumbria, UK (OS National grid reference NY680550, latitude 54° 52' 48.31" N, longitude 2° 31' 09.57" W, 180-595 m Above Ordnance Datum, Figure 1). The channel at this location has a Strahler (1952) stream order of 3, and drains a catchment underlain by Carboniferous sandstones, limestones, and shales, overlain by glacial diamict. The river channel displays pool-riffle and rapid morphology, with a mean bed slope of 0.031 m/m. In July 2007 an extreme rainfall event resulted in an estimated flood peak of 60 m³s⁻¹ (Milan, 2012), mobilising the full valley floor and initiating a peat slide in the headwaters. Many historic flood ‘berm’ deposits (~D50 200 mm) previously documented by Macklin et al. (1992), were re-mobilised by the flood. Immediately following the event the channel changed from a narrow 6 m wide single-thread sinuous channel with a well-vegetated valley floor into a multithread channel with a width in the region of ~25 m (Figure 2), and new boulder berms were deposited, following evidence of hyper-concentrated flow sediment transport processes (Milan, 2012).

3 METHODS

Detailed spatially distributed surveys of a 500 m reach of the Thinhope Burn have been conducted on a regular basis since 2003. Between 2003 and 2011 data were collected on four occasions using a Leica System 500 RTK sGNSS and on a further four occasions between 2014 and 2017, using a Topcon 2000 TLS fixed using tiepoints surveyed with a Leica System 1200 RTK dGNSS capturing the immediate geomorphic impacts of the 2007 flood event and recovery in the ten years following the event. The data were used to produce 0.1 m resolution DEMs with error filtered and point clouds processed following established protocols (see Heritage et al., 2009; Milan et al., 2011; Schwendel et al., 2012; Schwendel and Milan, in press); the main analysis of which will be presented in a full paper elsewhere. Here we concentrated on a 200 m sub-reach at the downstream end of the site, and compare cross-sectional and long-profile morphological developments, extracted from the DEMs, over the periods 2003-2017. The cross-section and long-profile positions are indicated on the reach DEM in Figure 1b. Aerial photographs taken from Google Earth and Zoom Earth, are also presented in Figure 2 and used to supplement information on channel change.

4 RESULTS

4.1 Aerial images

Planform changes to the river reach are shown in Figure 2. The pre-flood event image from 2003 shows a narrow sinuous channel, with gravel stored in point bars, and with a well-vegetated floodplain comprising grasses and bracken. Several terrace levels can be seen on the 2003 image, reflecting incision over the Holocene (Macklin et al., 1992), and a large boulder berm can be seen on the inside of the downstream-most meander, that was dated to a flood that occurred in 1929 using lichenometry (Macklin, 1992); and although
younger flood deposits were evident, the presence of this unit in 2003 suggests there had not been flood of a high enough magnitude to mobilise this unit since that date. The post-flood 2007 aerial image shows valley-wide stripping of vegetation from floodplain and terrace surfaces, where the lighter colour indicates the presence of exposed gravel. The active channel width has increase by around 300%, and there is evidence of small mid-channel bars as well as point bars. In many areas gravel and boulders were transported and deposited onto the floodplain (Milan, 2012). The 2012 image shows little sign of recovery. In contrast, there appear to have been further major changes, possibly in response to another large flood. The channel is clearly multi-thread in places, and the thalweg has shifted re-working material deposited in the 2007 event. There are large areas of unvegetated gravel still evident on the valley floor, with an extended active channel width, when compared to the 2003 image.

Figure 2. Aerial images sowing historical planform channel adjustments over the period if the investigation. 2003, 2007 images (source: Google Earth), 2012, 2015 images (source: Zoom Earth).

4.2 Cross-sectional change

Cross-sectional morphological changes for the two cross-section locations shown in Figure 1b, are indicated in Figures 3 and 4. Both cross-sections run across successive meander bend apices. For cross-section 1, the 2007 event appears to have caused erosion of the right bank and substantial deposition (2 m) on the inside of the bank; coinciding with the location of the fresh boulder berm deposit reported in Milan (2012). There was also some stripping of an old berm deposit with around 0.5 m of change, further inside the meander. Only small adjustments take place between the 2008 and 2011 surveys, with some further erosion of the right bank. However, the 2014 survey shows further significant change with removal of around 1 m of the berm deposited in 2007, and around 1.5 m of aggradation in the main right channel. This is likely to correspond with the changes shown at this location between the 2007 and 2012 images in Figure 2, and is likely to relate to an event between 2011 and 2012. The changes between 2014 and 2016 (Figure 3b), show relatively minor adjustments, however the 2017 survey shows notable change with around 0.5 m of deposition on the inside of the meander and further erosion in the location of the 2007 berm deposit; at this location in the order of 1 m of erosion has occurred since 2011.
Figure 3. Morphological change over the study period for Cross-section 1 (location shown in Figure 1b), a) changes for 2003-2014, b) changes for 2014-2017.

Figure 4 shows morphological adjustments across the meander apex further downstream, at cross-section 2. Major change takes place in response to the 2007 flood, with the removal (2 m) of part of a lower terrace and the 1929 berm deposits that formerly sat on top of this. A new mid-channel berm is also evident with around 1 m of deposition at between 5 and 7 m across the section. The bed level fills up with sediment at between 15 and 25 m across the section, as shown on the 2008 and 2011 surveys. The 2014 survey indicates significant change, as also indicated at cross-section 1 upstream. Substantial deposition has taken place on the inside of the meander in the area 15 to 25 m across the section, that had been showing a depositional trend in the previous two surveys. A fresh channel has been cut between 7 and 16 m across the section. Deposition has also taken
place towards the left bank. Vertical adjustments are evident between 2014 and 2017, with deposition taking place in 2016 and 2017. At this location the bed has aggraded by just over 1 m since 2007.

Figure 4. Morphological change over the study period for Cross-section 2 (location shown in Figure 1b), a) changes for 2003-2014, b) changes for 2014-2017.

4.3 Long-profile changes
The long profile morphological changes are demonstrated in Figure 5. The long profiles follow the line of the 2003 thalweg shown in Figure 1b. It is clear that the full reach experienced in the region of 2 m of vertical erosion almost along the full length of the thalweg following the 2007 event, with the exception of a region about
80 m downstream along the profile; where the elevation remains almost constant throughout the duration of the investigation. It should also be noted that substantial deposition also took place elsewhere within the reach, such as the berm deposit noted in Figure 3a. A trend of sedimentation and increasing bed elevation is shown between 2011 and 2014 in the downstream 70 m of the reach. This continues at between 110 and 150 m along the reach up until the most recent 2017 survey. There is a notable increase in bed elevation in the 2014 survey at around 60 m downstream, possibly representing a slug of sediment that has stalled in the channel in the proximity of the meander. This is also detected in cross-section 1 at between 25 and 35 m across the channel. This bedform appears to be maintained on the long profile up until the 2017 survey Figure 5b. The upstream 50 m of the study reach also shows more uniform deposition in the 2014 survey, following scour after the 2007 flood, but becomes more stable between 2014 and 2017.

Figure 5. Morphological change over the study period for the long-profile following the line of the 2003 thalweg (location shown in Figure 1b), a) changes for 2003-2014, b) changes for 2014-2017. Cross-section 1 (Figure 3) intersects the long profile at 13 m and cross-section 2 (Figure 4) at 83 m downstream.
5 DISCUSSION & CONCLUSIONS

Past work on historic flood deposits at Thinhope Burn (Macklin et al., 1992), indicates that numerous large floods capable of mobilising large boulders and sediment volumes have occurred in the past 250 years; Macklin et al. (1992) were able to identify links between boulder deposits and 21 different flood events since 1766. Although geomorphologically effective events occurred more frequent between 1780-1820, 1840-1880, and 1920-1950, corresponding with hydroclimatic changes evident in the UK during those periods, it may be concluded that big floods tend to generate a morphological response at least once every 10-20 years. Milan (2012) notes that the neighbouring catchments to Thinhope Burn (the Knar Burn, and Glendue Burn) failed to show a response to the 2007 event, possibly indicating the focused nature of the intense rainfall, but also suggested that Thinhope Burn was more geomorphologically ‘sensitive’ (sensu Brunsden and Thornes, 1979) than its neighbours. The 2007 flood appeared to be the most significant since 1929, as this was the first to fully mobilise the 1929 berm dated by Macklin et al. (1992).

Ten years after the 2007 event, the valley floor of Thinhope Burn still does not appear to show a trend towards recovery, and does not currently look set to return back to the pre-flood condition. Significant channel adjustments, with vertical changes of between 0.5 and 2.5 m are evident from cross-section resurvey data. Following the 2007 flood, some years show less change, yet significant changes occurred between 2011-2014, probably in response to another large flood between 2011 and 2012. Although no flow data exists for the Thinhope catchment, the lack of flood strandline evidence (used to reconstruct the 2007 peak flood magnitude) would suggest that this was of a much lower magnitude. In its current disturbed state, the Thinhope catchment is likely to be much more responsive to floods. Much more unconsolidated sediment is available due to vegetation stripping and bedload mobilisation in the 2007 event, and until this once again becomes stabilised with vegetation, bedload transport rates are likely to be much greater than the pre-2007 condition. The cross-sections and long-profiles show an overall trend towards aggradation since 2014, suggesting the passage and temporary storage of sediment from higher in the catchment where it was mobilised in 2007. The channel is likely to remain dynamic, and one which is likely to respond to lower magnitude floods, due to the lower threshold for motion resulting from the loose structure of the sediment and the shear availability of material for sediment transport.

There is some evidence that river flows in the UK are following climate change predictions, although this is not fully conclusive (Hannaford and Buys 2012). These workers demonstrate that the strongest increases in runoff are evident for the winter half of the year in upland, northern catchments, while autumn runoff has increased across much of the UK. Bearing this in mind, catchments in the uplands of northern England are particularly susceptible to increased flows. Those catchments that are more sensitive in nature, such as Thinhope Burn, are therefore more likely to be pushed close to a threshold condition; whereby significant channel and floodplain changes take place, with transport of very high volumes of sediment. We conclude that a better understanding of relative catchment sensitivity and the potential implications of climate-change induced increases in flows upon those catchments is needed to plan for the potential impacts of enhanced sediment loads upon flood risk.

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REFERENCES


