Reconstructing long-term flood histories for Cumbria

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Introduction

River flooding imposes severe social, economic and environmental impacts on communities and the landscape. Flooding is a particularly emotive topic in Cumbria: the storms that swept through northern England in December 2015 (Storms Desmond, Eva and Frank; Figure 1) delivered record-breaking amounts of rainfall and severe flooding, and followed floods in 2005 and 2009 that had similar impacts. Each devastating flood prompts residents, policy makers and scientists to pose fundamental questions: are floods becoming more frequent in Britain? Are individual floods becoming more severe? How is anthropogenic climate change altering flood regimes? Has our use of the landscape increased flood risk in a catchment? Furthermore, climate change is increasing the moisture-holding capacity of the atmosphere and UK Climate Projections 2018 (UKCP18) indicate more intense winter rainfall in northern Britain in coming decades. Trends and drivers of flooding are urgent and very active areas of research but providing definitive answers for these questions is an enormous challenge. One major barrier is the relatively short duration of river flow data available for analysis.

The UK has impressive hydrological recording infrastructure. The National River Flow Archive (https://nrfa.ceh.ac.uk/) archives data from approximately 1,500 gauging stations. Isolated discharge measurements were made across the UK in the 19th and early-20th centuries, and the Thirlmere Reservoir outflow has been monitored since 1935. The national network came online in the 1960s, however, when gauging station installation expanded rapidly under the stewardship of the Water Resources Board (Lees, 1987). Instrumental river flow data underpin flood frequency analysis and return period calculations, which aim to give a measure of the probability of occurrence of a flood of known magnitude (discharge). The 40-year operational lifespan of most gauging stations means there is every chance the highest highest-magnitude floods, which are by definition also the rarest, are missed. Peak flow return periods for rivers across Cumbria were revised after each of the major floods in 2005, 2009 and 2015 (e.g. Miller *et al.* 2013) because each new datapoint extended the range of known flow magnitudes. Longer time series are evidently needed to capture the full range of hydrological variability a catchment can experience and judge the extent to which 21st-century flooding has been unprecedented.

Scientists are turning to alternative sources of hydrological data to extend flood records further back in time. The British Chronology of Hydrological Events (http://cbhe.hydrology.org.uk/), for example, is a freely accessible and expanding repository of historically-documented floods (and droughts). Other researchers, including ourselves, are assessing the potential for lake sediment records to be an untapped archive of major floods events spanning centuries and potentially millennia. This paper summarises our recent findings on flood trends and drivers in Cumbria using long-term hydrological data harvested from lake sediment records at Brotherswater and Bassenthwaite Lake and historical information, namely documentary records and physical flood marks, from the River Eden catchment.

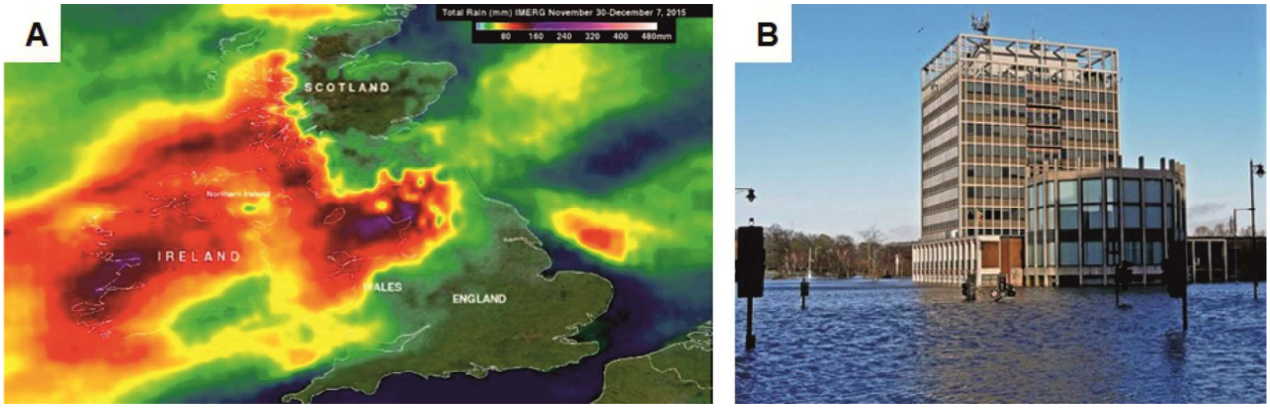


Figure 1. A) Satellite-derived rainfall totals for 30 November – 7 December 2015 (NASA). B) Carlisle Civic Centre on 6 December 2015 (photo credit: Rose and Trev Clough).

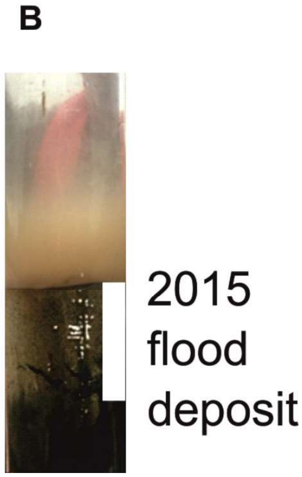


Figure 2. A) Sediment core image showing lighter layers richer in mineral material and darker sediments that contain higher organic matter content. B) A lake sediment core revealing the thick mineral unit deposited by floods during Winter 2015.

How do lakes record past flood imprints?

Lakes act as a natural trap for material eroded from the catchment. Since the last ice retreated approximately 12,000 years ago, lakes across Cumbria have accumulated thick (up to 10 metres) sediment deposits at their beds. Sediments comprise mineral material transported from hillslopes and riverbanks plus an organic component that includes algal productivity and other internal biomass (Figure 2).

In the 1930s, Filip Hjulström graphically illustrated the empirical association between river flow velocity and the size of mineral particles that can be eroded, transported and deposited (Figure 3). Assuming particle density and shape remains constant, a river under flood conditions has the capacity to move particles of larger diameter. River flow decelerates upon entering the lake, causing large entrained particles to be released from active suspension and settle vertically through the water column to the lake bed. When the river returns to normal flow conditions, these thin flood layers containing coarser particles are continually covered by the finer-grained sediment matrix and a diagnostic depositional imprint of a past flood is preserved. Extracting a long basal sediment core containing numerous thin flood layers can therefore produce a flood reconstruction extending much further back in time than instrumental data: centuries and potentially

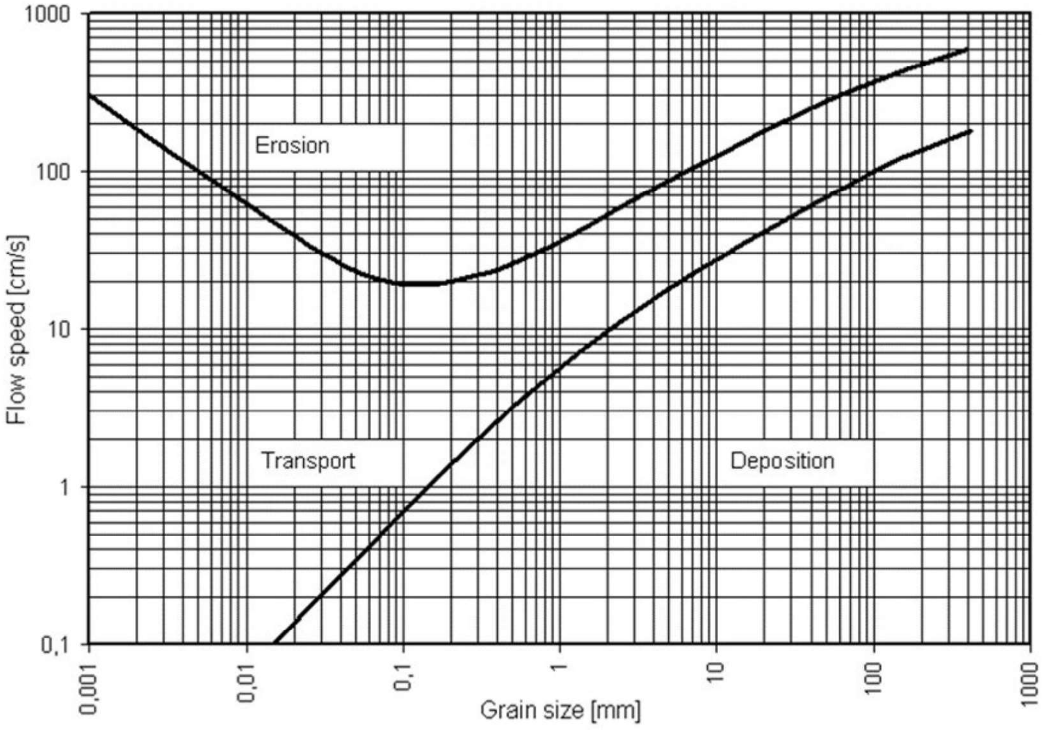


Figure 3. Graphical depiction of the Hjulström curve, showing the interaction between river flow, sedimentation processes and particle size. Source: Wikicommons (Karrock)

millennia. We have published investigations from Brotherswater (Schillereff et al. 2019) and Bassenthwaite Lake (Chiverrell et al. 2019), with work underway at Buttermere, Ullswater and Thirlmere Reservoir.

How certain are we that lakes preserve individual flood deposits?

The hydrological and geomorphological processes connecting catchment erosion to sedimentation in a lake are highly complex. Indeed, in many lakes flood deposits are indistinguishable from the background sediment matrix, so potential study sites must be chosen carefully. Brotherswater meets many desirable criteria (Figure 4). It has a single inflow so we can be confident of the catchment-source area. Its deep, flat central basin minimises the potential for previously accumulated sediments to be re-suspended, which blurs the stratigraphic record. Surface waves can trigger re-suspension in shallower lakes, for example. Brotherswater has a high catchment area:lake area ratio and steep slopes with bare, shallow soils quite susceptible to erosion; these characteristics ensure ample sediment delivery.

Our next step is demonstrating that high-magnitude flows deliver measurably different sediments to the lake today. Establishing the contemporary depositional mechanisms will reinforce our interpretation of the long sediment record. We deployed sediment traps in Brotherswater for 18 months to collect current sedimentation and explore the relationship between sediment patterns and variations in incoming river discharge. Simple sediment traps, comprising upright 75-cm cylindrical drainpipes connected to 500 mL capturing containers (Figure 5), were moored at two positions (one near the inflow, the other in the lake centre) and three water depths to measure the volume and calibre of incoming sediment under different flow conditions and track the movement of the sediment plume around the lake basin. Each trap was recovered on a near-monthly basis, the amount of sediment and particle size of each sample was measured and compared to local river flow data. The nearest gauging station was Patterdale Side Farm on Goldrill Beck. Gauging stations progressively downstream record similar hydrological time series so we are confident it is representative.

We found at Brotherswater that a hydrological threshold governs whether a flood lamination will be preserved at the lake bed. Catchment geomorphological processes mean the link between higher river flow and the size of transported material is complex and non-linear. For example, the level of fluvial connectivity between the catchment and lake is important. Is eroded sediment transported efficiently by the river and deposited in the lake during a single flood event? Lags in this connectivity will alter the magnitude-deposit relationship. We identified a river flow threshold whereby only higher-magnitude events transported adequate material for a flood deposit to be preserved at the lake bed. Below this threshold, however, the near-continuous deposition of smaller clay and silt particles, plus biological deposition, masks the flood imprint. Essentially, a sediment core extracted in the future would not contain sedimentary evidence of any flow below this hydrological threshold.

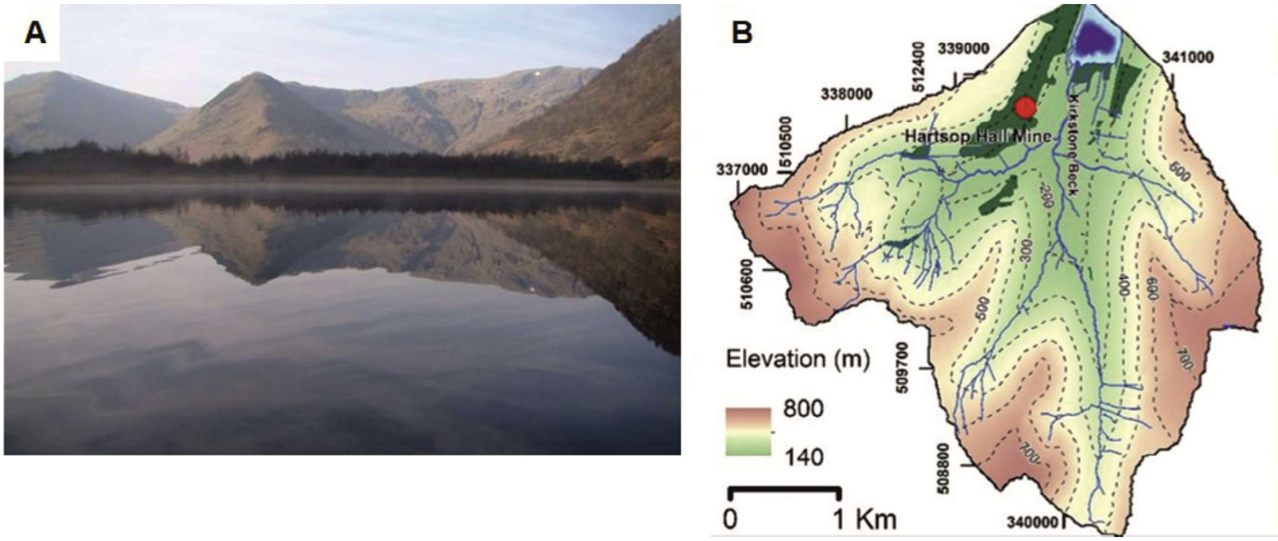


Figure 4. A) Looking south at the bare, steep slopes of the Brotherswater catchment. Inflow enters at southwest corner (far right of this view). Photo credit: Daniel Schillereff. B) Extent and topography of the Brotherswater

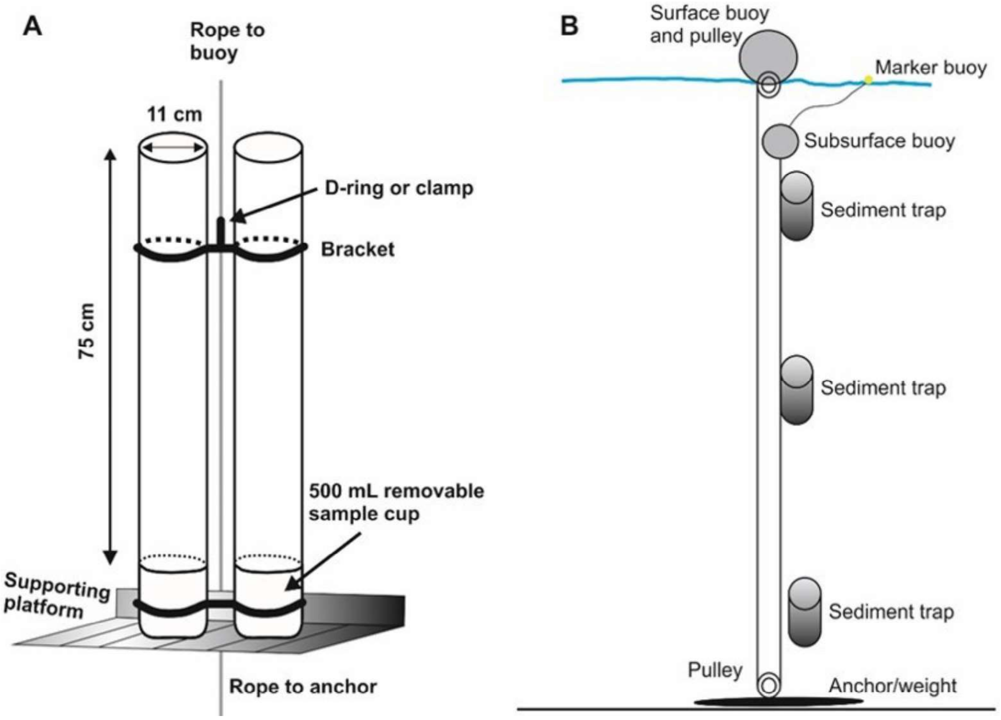


Figure 5. Diagram of sediment trap design (A) and mooring setup (B) for the sediment trap deployment at Brotherswater. Redrawn from Schillereff (2015).

We extended this calibration by comparing river gauging station data since 1961 to the recent sediment record. Similar thresholds were identified, which we attributed to sediment starvation. This describes a scenario whereby a large flood will flush the catchment of sediment. Should a second major flood hit the area within the next two years, insufficient sediment is available for transport and no flood deposit will be preserved in the lake, even if event magnitude is extremely high. This is another key uncertainty that must be considered when interpreting lake palaeoflood records.

Reconstructing 1500 years of flooding at Brotherswater

We recovered three sediment cores from Brotherswater that were between 1.5 and 3.5 metres in length. Our age-depth model indicates these sediments were deposited over the last 1500 years. The timescale of deposition was determined using radiocarbon, ^{210}Pb dating as well as chronological markers linked to the lead mining history in the Brotherswater catchment. Cumbria has a well-documented history of vast mining activity over the last few centuries and surface spoil heaps are common (Figure 6). Lead, zinc, copper and baryte were widely extracted, including at Hartsop Hall Mine, and we can tie rates of ore extraction to peaks in metal concentrations in the lake sediment profile. Fossil fuel emissions have altered the atmospheric composition of ^{14}C and reduced the usefulness of radiocarbon dating for samples spanning the Industrial Revolution (i.e., since 1750 AD). The mining markers fill this gap. The phased extraction of different metals since the 17th Century at large mines in the Bassenthwaite Lake catchment also enhanced the chronology developed for its lake sediment record (Chiverrell et al., 2019).

Systematic particle size measurements along each sediment core showed the sediment matrix contains three distinct groupings. Two finer end-members (clays to fine silts) are prominent throughout the core and reflect near-constant sedimentation from hillslope deposits and river banks. The third grouping is much coarser (fine to medium sand on the Wentworth-Udden scale; Figure 7) and sporadically punctuates the sediment record. We interpret sediment layers dominated by this end member to reflect deposition under flood conditions.

We identified 88 individual flood layers over the last 1500 years. A key finding is that floods do not occur at regular intervals. Instead, they cluster into phases with frequent flooding and other periods of quiescence (Figure 8). Each phase typically lasts a few decades although the 12th-14th centuries saw a prolonged spell of minimal flooding. This flood-rich, flood-poor pattern has been seen in hydrological datasets all over the world. Indeed the Brotherswater reconstruction shows a trend towards more frequent

Figure 6. Looking west across the Brotherswater floodplain. Surface spoil heaps are visible on the far slope. Image credit: Richard Chiverrell.

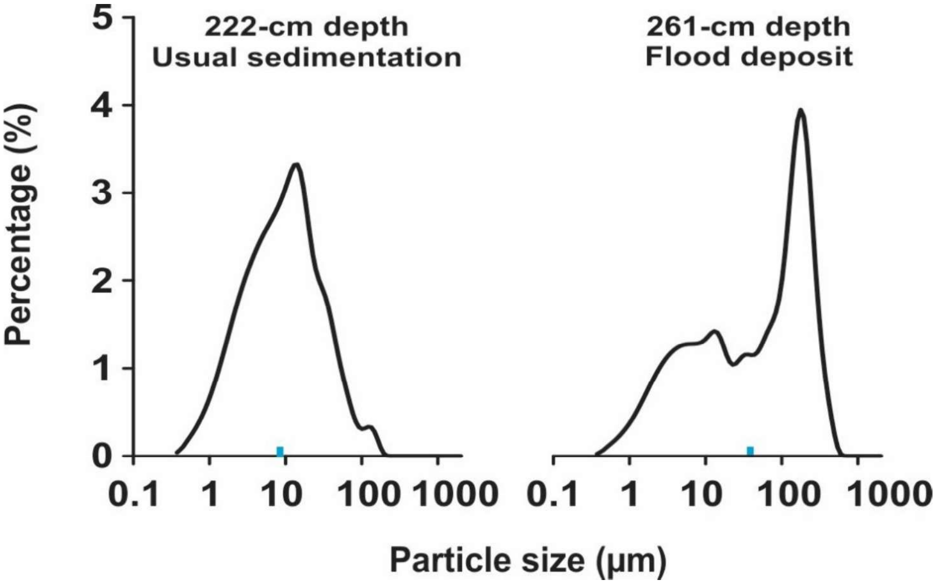
flooding in the last several decades. This could be a protracted flood-rich phase, a response to anthropogenic climate change or a consequence of human modification of the catchment.

Flood drivers: climate versus human activity

In the Brotherswater flood reconstruction, shifts between flood-rich and flood-poor phases coincide with variation in the North Atlantic Oscillation (NAO). The NAO is a large-scale process related to changes in atmospheric pressure over the North Atlantic and we found a statistically significant link over the entire 1500-year record. We also identified a temporal association with the Atlantic Multidecadal Oscillation, a natural cycle reflecting changes in Atlantic sea-surface temperatures. A better understanding of the role of natural cycles is an essential precursor to exploring how anthropogenic climate change may be modifying flood patterns.

The long history of human occupation in Cumbria is a crucial but complicating factor. There is solid

Figure 7. Typical particle size distributions for two sub-samples from a Brotherswater sediment core. The left-hand distribution is largely fine-grained (mean = 9 µm) and represents the usual sediment matrix (river under normal flow conditions). On the right is a flood deposit, which contains some fine material but the sand component is dominant (mean 40 µm). Note the x-axis is plotted on a logarithmic scale.



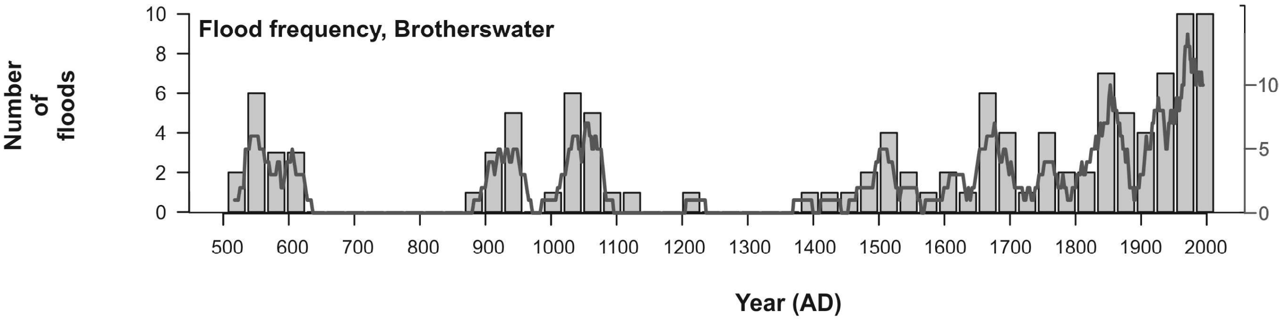


Figure 8. Time series of flood frequency at Brotherswater. The number of coarse flood layers were summed into climatically representative 30-year bins. The dark grey line is the 31-year running sum. Modified from Schillereff et al. (2019).

archaeological evidence of anthropogenic land-use since the Neolithic (5000 years ago). Data from a range of sources including pollen records, phases of rapid gully incision on hillslopes and accelerating lake sedimentation rates illustrate the scale of human modification in the last two millennia. Woodland clearance, the expansion of sheep farming, manual river straightening and other forms of floodplain management have a long history in Cumbria. More flood deposits are recorded in the Brotherswater record during periods of known settlement and land-use, including the Anglo-Saxons, Norse occupation, upland repopulation and the expansion of mining activity. These factors will have altered the hydrological and sedimentological connectivity in the catchment. This makes it difficult to deduce the relative importance of climate versus human activity in explaining the trend towards more frequent floods in recent times (Figure 8) and cannot be used for flood frequency analysis. We successfully used lake sediment data to refine return period estimates for Bassenthwaite Lake as it had a much larger catchment and lower intensity of historical land-use (Chiverrell et al., 2019). This quantitative assessment also based on particle size data indicate 21st-century floods are the largest for more than five centuries.

Reconstructing floods in the River Eden catchment using historical evidence

Brotherswater lies in one headwater of the larger River Eden catchment (total area ~2300 km^2), which drains much of the northwestern-most section of England from its source at Black Fell Moss, Mallerstang, in the Yorshire Dales, through to the Solway Firth. Towns along the Eden including Appleby, Penrith and the City of Carlisle have all suffered badly during recent floods. The Eden catchment contains a long and rich written history that documents numerous major flood events in previous centuries, especially for Carlisle. Similarly, a set of flood marks have been engraved into the Eden Bridge since 1822. An initial comparison of 21st-century flood magnitudes to historical flood data shows the flood level in 2005 (1516 m^3 s^{-1}) was determined to be one meter higher than the previous highest mark from 1822, while the 2015 event (1677 m^3 s^{-1}) was 0.6 m higher again than 2005 (Environment Agency, 2016).

Historical evidence can usually be used to determine the timing of past floods (e.g., the date may be recorded in a pastor's diary entry) but there is potential to estimate flood magnitude. Smith and Tobin (1979), for example, mapped the flood extent of flood events between 1800 and 1968, with a ranked series of 49 major floods at Carlisle. The largest floods are also marked on Eden Bridge, which Macdonald and Sangster (2017) used to estimate discharges for the 1822 (~1125 m^3 s^{-1}), 1856 (~1060 m^3 s^{-1}), 1925 (~1000 m^3 s^{-1}) and 1968 (~930 m^3 s^{-1}) floods (Figure 9).

Extracting hydrological data from written records becomes more uncertain further back in time but valuable information can nevertheless be derived. The floods of 1771 were particularly extreme across the UK, for example, and whilst records suggest it was not as destructive in Carlisle, an account by Garret (1818) recalls loss of bridges over several of the principal tributaries and livestock lost. Additional floods are also recorded in 1684, 1685, 1710 and 1763 (Chronology of British Hydrological Events, Black and Law, 2004), although insufficient details limit our capacity to estimate discharges for these events. The snowmelt flood of 1767 is well-documented in the accounts of the Bishop of Carlisle (Todd *et al.* 2015), illustrating how historical records can shed light on flood-generating mechanisms. There is some material detailing the 1360 flood, with Jervoise (1931) noting the old bridge over the Eden being destroyed and Bishop Welton of Carlisle providing indulgences to those repairing the bridge (Ferguson, 1893). Other accounts in the early nineteenth century recall the

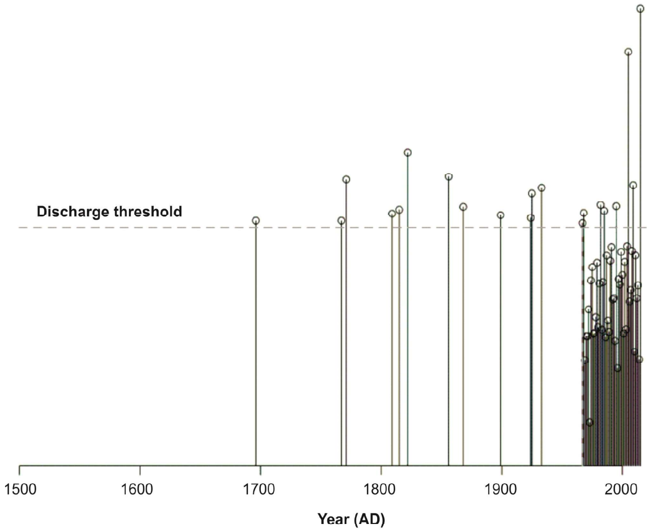


Figure 9. Time series of flood discharges in Carlisle reconstructed from historical evidence merged with measurements from the Sheepmount river gauging station (1967-2015). The two exceptionally high values are 2005 and 2015.

remains of the 'old bridge' as still being visible.

We incorporated flood discharges estimated from historical evidence into a flood frequency analysis (FFA) for Carlisle to illustrate the scope of this approach to augment conventional calculations based solely on river flow data. Three different methods were applied, reflecting different levels of availability and confidence in the data (Figure 10), following the approach used by Macdonald *et al.* (2014) for Lewes in southeast England. Pre-1650 floods are excluded because substantial changes in catchment and channel morphology may have introduced considerable uncertainties into discharge estimates.

Gauged data only: a single site analysis based on 48 Annual Maximum Flood Events in the gauged series from Sheepmount station on the Eden at Carlisle (1967 -2015);

Historical + gauged, known discharges: A flood frequency analysis of the combined record considering the peak discharge of the historical events to be exactly known from 1650 to 2015;

Historical + gauged, above-threshold discharges: Flood frequency analysis of the combined record considering the peak discharge of the historical events to be unknown but known to exceed a defined perception threshold (Binomial censored data), 1650-2015.

The most important finding is that incorporating historical flood information into the FFA lowers the return period estimates for high-magnitude floods (Figure 10). The two very large recent floods dramatically increase the Method 1 values (red line on Figure 10). Including many more floods spanning centuries rather than only four decades provides much greater confidence in the return period calculations for the largest and rarest floods. That the two methods using historical data (black and blue lines on Figure 10) provide comparable results is also reassuring. The extended flood series (Figure 9) does emphasise that the 21st-century floods that have had such drastic impacts in Cumbria had particularly high magnitudes. This fits with data from Brotherswater (Schillereff *et al.* 2019) and Bassenthwaite Lake (Chiverrell *et al.*, 2019) sediment records. It is possible we are experiencing a flood-rich period as witnessed repeatedly in past centuries but the magnitude of the recent events is striking when viewed in the long-term context provided by sedimentary and historical datasets.

Conclusions

This paper presents an overview of recent research using alternative archives of hydrological data to reconstruct the frequency and magnitude of floods in recent centuries for Cumbria. We've shown that lake sediment records and historical information can provide vital context for evaluating how anomalous the recent major floods may be, which is timely given climate change projections suggest regional flood risk will continue to escalate. There are a range of limitations to our palaeoflood reconstructions and efforts are underway to refine our data. For example, we are expanding the number of lake palaeoflood studies in Cumbria to build a regional picture of trends in flooding. This will allow us to more accurately inform discourse around the "unprecedented" nature of recent flooding in Cumbria.

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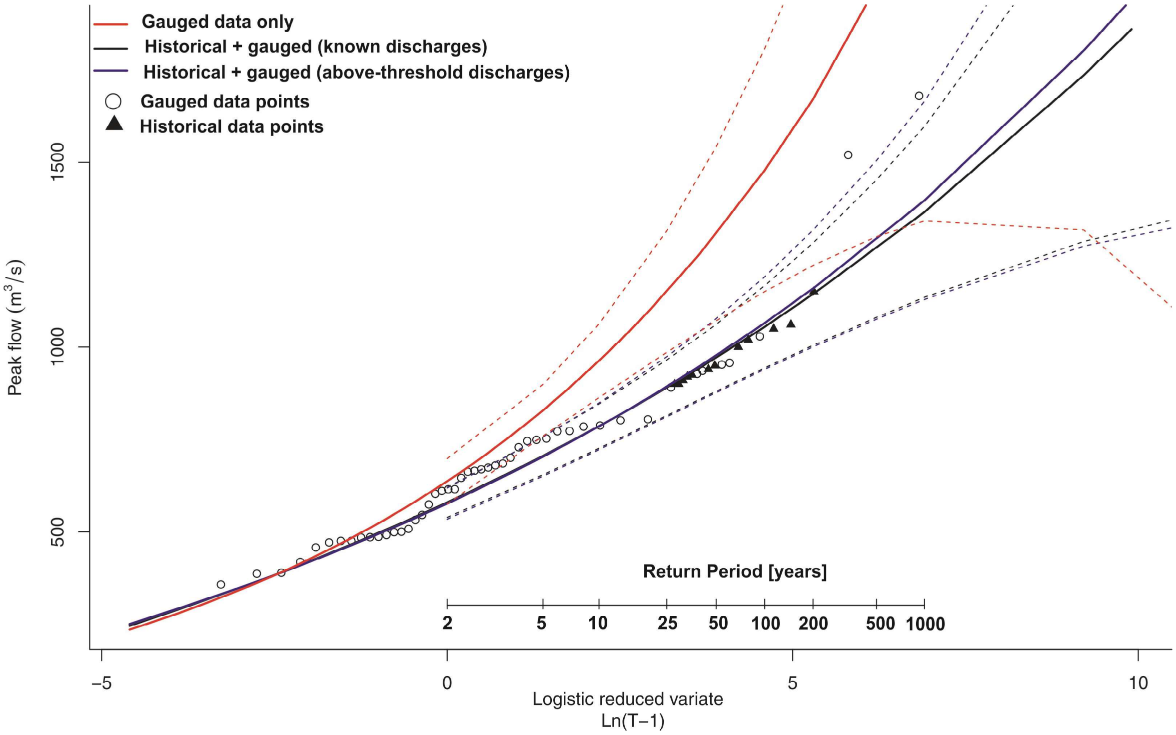

Figure 10. Flood frequency analysis for Carlisle. Open circles and filled triangles are the maximum flow in a given year from gauged data and historical records, respectively. The solid red line is the return period estimate calculated solely based on gauged river flow data (Method 1) whereas the blue and black solid lines incorporate the historical data (Methods 2 and 3). Dashed lines represent the 95% confidence interval for each method.

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