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Understanding river channel sensitivity to geomorphological changes

Influence of valley confinement and flood plain infrastructure on morphological river changes during extreme flows

FRS17183/R3

Flood and Coastal Erosion Risk Management Research and Development Programme

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Author(s):
Sear DA, Hornby DH, Wheaton J and Hill CT

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Research contractor:
University of Southampton, GeoData Institute,
Southampton, SO17 1BJ. Tel 023 80 592719

Environment Agency's Project Manager:
Paul Weller

Theme Manager:
Owen Tarrant, Asset Management

Collaborator(s):
Utah State University

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Professor Doug Wilson
Chief Scientist

Executive summary

Background and aims

Extreme flooding in the UK in the last decade (for example, the Storm Desmond floods of 2015) has highlighted that it can impact significantly on sediment transport processes (erosion and deposition) and alter the shape and position of river channels.

This study aimed to find ways to identify where river channels are sensitive to change in both normal and extreme flows in England and Wales, and to better understand the factors that influence that change.

Research approach

This study is documented in 4 reports:

- Report 1: Literature review and understanding factors that influence river channel change (FRS17183/R1)
- Report 2: Developing and evaluating methods to identify erosion, transport and deposition on a national scale (FRS17183/R2)
- Report 3: Influence of valley confinement and flood plain infrastructure on morphological river changes during extreme flows (this report, FRS17183/R3)
- Report 4: Creating pilot data sets showing potential for erosion across England and Wales using the shear stress data mining method (FRS17183/R4)

This is report 3 and describes the work carried out to:

a) better understand the impact of confinement and constriction on geomorphic change

b) develop and test a suite of tools that can estimate the risk of geomorphic change in extreme floods (defined as probability of occurrence >0.2%) that could be applied at a national, regional or catchment scale

c) test the tools on 2 catchments where there is enough data

Although the tools have been developed for extreme flows (0.2% annual exceedance probability (AEP)), they could also be adapted to predict the risk of geomorphic change in less extreme floods (for example, 1% AEP).

Main findings

We know from research that development of the flood plain, including legacy infrastructure such as railway embankments, communications routes and development, has changed the hydraulics of extreme floods, creating conditions that can amplify geomorphic changes (Lewin 2013, Wong and others 2014, Comiti and others 2015).

This information, supported by using certain tools, can help flood risk managers identify the risks geomorphic change presents during extreme flooding or the impacts of development proposals on future risk.

The analysis has identified a set of important points that are relevant to flood risk management and wider planning.

- For UK rivers, the value of unit peak discharge (Q_{peak}) of 1.0 $m^3s^{-1}km^{-2}$ marks a threshold above which geomorphic change is likely in most types of channel, and that the magnitude of change increases with unit peak discharge above this threshold. It is therefore possible to estimate the peak discharge above which geomorphic change is likely based solely on catchment area.

- In UK rivers, geomorphic changes during extreme (<0.2% AEP) floods are strongly influenced by confinement expressed in 2 measures – the area of sediment supply available to a reach and the gradient of stream power. Combined, they explain 74% of the variance in observed geomorphic change in the Derwent case study river and can predict 52% of the observed geomorphic change across 2 floods in 2009 and 2015.

- A set of tools has been developed that can predict the risk resulting from geomorphic change during extreme floods. These tools cannot currently be used on a national scale, but the project has identified how they could be modified to generate national risk maps.

- The risk modelling revealed differences between the River Kent and River Derwent. The Kent flood plain has a lower risk profile compared to the Derwent, which results from lower magnitudes of predicted geomorphic change coinciding with lower intensity land uses.

- The effect of human modification to the flood plain of the River Derwent, Cumbria over the past 150 years, has increased the scale and location of geomorphic change relative to natural conditions.

- In a hypothetical analysis, removing or redesigning existing flood plain infrastructure (road and legacy rail embankments) along the River Derwent flood plain removed the ‘very high’ risk class and reduced the ‘high’ and ‘moderate’ risk classes, resulting in an overall reduction in risk of geomorphic change.

Recommendations

The current tool, although being used, cannot be applied at a national or catchment scale without being developed further. To achieve this, 3 steps need to be taken:

- simplify the existing method to work with UK existing national data sets to automatically generate confinement, constriction and erodibility at 500 m reaches. This type of tool will need to account for branching channels and tributary junctions

- change to using discharge and water surface elevations for 0.2 and 0.1% AEP flood model outputs to generate stream power gradient

- generate a set of new geomorphic change data sets based on air photos suitable for testing the MCA model. Examples could include the South Tyne (post 2015 floods) and the Eden/Caldew (post 2015 floods).

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1.1 Background

Extreme flows may be caused by several processes, from extreme precipitation associated with extratropical storms, rapid snow melting or intense and often localised rainfall associated with convective storms, typical of summer weather patterns, and by excess soil moisture.

There is evidence that precipitation patterns are shifting with increasing 5-day intensities, increasing extreme wet days against 1961 to 1990 and 1981 to 2010 averages and increasing consecutive wet days (Kendon and others, 2018), acting as influences of changing flows and flood characteristics.

Simulations of 21st century climate change scenarios project an increase in the frequency of extreme events, including an increasing intensity of precipitation extremes (O'Gorman and Schneider, 2009). These are expected to produce substantial river discharges and exacerbate flooding still further, with flood hazard and associated costs projected to increase significantly (Hallegatte and others, 2013, Stocker, 2013). For example, in the UK the costs of flooding during the winter of 2015 to 2016 were estimated at £1.6 billion. This included damage to infrastructure, properties and maintenance of channels and flood defence assets (Environment Agency 2018).

Naturally, attention has tended to focus on the risk and impact of flooding on people and associated infrastructure and businesses (Hall and others, 2014). However, floods are events in which major geomorphological changes naturally occur and in which fluvial systems transport sediments. So, they are also fundamental to the development of physical habitat and aquatic ecosystems more generally. They provide ecosystem services, and are a necessary part of the natural rock cycle, connecting terrestrial sources to the coast (see Hooke 2015, Sear and others, 2010).

The geomorphic changes associated with transporting sediment during flood events have impacts other than those arising from inundation by water. These include erosion of land, loss of infrastructure, deposition on urban and agricultural land, and changes to physical habitats (see Magilligan, 1998, Comiti and others, 2016, Death and others, 2015).

Human modifications to flood plains, river channels and the wider catchment result in changes in the natural flooding processes that, in turn, change the risks to infrastructure, property and livelihoods caused by erosion and deposition (geomorphic change) (see Lewin, 2013, Sear and others, 2000).

While research to date has provided ample evidence of the mechanisms and magnitude of geomorphic change during extreme floods (see reviews by Kochel, 1988, Carling and Beven, 1989), these have tended to be specific to the event and geomorphic context. With recent extreme flooding occurring more frequently, resource managers want to be able to better forecast the impacts of extreme events, and would like better tools to help them plan disaster response and recovery (Huntingford and others, 2014, Pattison and Lane, 2012, Chiverrell and others, 2019, Hooke, 2015, Van Appledorn, 2019).

To contribute to this, those working in the area of geomorphology must move from detailed studies of specific flood impacts to better predicting risks to people, property and infrastructure, ideally without needing complex, expensive and uncertain morphodynamic modelling (Buraas and others, 2014). To do this, the links between scales of geomorphic controls and response need to be better understood. There also needs to be less emphasis on the detail of the products, and more on the processes during the flood event that contribute to geomorphic change and risk to people, property and livelihoods. Since flood plains are typically the most populated areas in a catchment, any improvement in predicting how channels respond to extreme events will be beneficial.

1.2 Aims and objectives

The winter floods of 2015 to 2016, like those in 2009 and 2010, resulted in costly damage to roads, bridges and farmland (Environment Agency, 2018, Joyce and others, 2018). Research carried out on the River Derwent in Cumbria after the 2009 floods (Sear and others, 2017, Wong and others, 2014, Joyce and others, 2018) considered how the pattern of natural and man-made confinement (such as roads and legacy railway embankments) of a flood plain affected flood risk during extreme floods. During these large events, flow patterns become modified by infrastructure and natural patterns of confinement, resulting in erosion and deposition that, in turn, influence flood risk. It was demonstrated that man-made confinement significantly increased stream power locally. This resulted in excessive riverbank and cliff erosion and deep bed scour, causing bridges to fail. Large amounts of sediment and gravel were also deposited, blocking channels and covering flood plain farmland, resulting in high recovery costs.

The same processes occurred during subsequent flooding in 2015, often in the same locations, leading to the same erosion and gravel deposition problems. This suggested that it might be possible to predict areas at risk of extreme flood erosion and deposition, and to identify opportunities to reduce these risks. This would help the Environment Agency and other interested groups planning infrastructure and land management/land use in flood plains to understand:

- the main factors affecting the location and scale of erosion/deposition in channels during extreme and normal flows
- how to predict channel changes to inform future flood risk management
- how to adapt existing, and improve future, design of infrastructure on flood plains to account for their effects on extreme flood flows and channel adjustments

Channels change over time and this can alter flood risk. Predicting change is currently difficult as there aren’t the tools or data sets available to consistently account for these changes in flood risk assessments or operational activities. Furthermore, climate change (more extreme flows and frequency of extreme flows) is likely to make these issues more significant and widespread.

Therefore, the objectives of this project were to:

- review the literature on extreme flood effects on channel and flood plain morphology
- analyse the River Derwent, Cumbria and River Kent case studies to determine the significance of channel confinement and human confinement on the risk of geomorphic change
- develop a methodology to predict the risk of geomorphic change from confining margins that could be apply to different types of river

Through these objectives, the project supported a wider project ‘FRS17183 Understanding river channel sensitivity to geomorphological changes’. This project aimed to identify ways to produce a picture of the geomorphological sensitivity of rivers in England and Wales in current and future climates and to test it on case study catchments. The results could be used alongside other approaches to support asset and channel maintenance activities, flood risk assessment, incident response, and long-term investment planning. This work could help to guide the design of future infrastructure.

1.3 Expected outcomes

1.3.1 Summary

The project delivered outcomes to achieve the aims. The project:

i. identifies whether valley confinement and flood plain infrastructure influence the scale of river sediment change in the River Derwent, Cumbria and other locations, and can help to predict channel sensitivity nationally. This can help to better understand where risk of erosion is increased due to changes in flood plain topography
ii. highlights which specific local factors (such as roads, railway embankments, degree of confinement) determine the scale of influence. These can be used to map hotspots of locations at risk both locally and nationally
iii. supports an evidence base to help flood risk managers prioritise investment to mitigate future risk and inform interested groups of options for mitigating risk such as reducing confinement due to legacy infrastructure

2 Literature review

2.1 Defining floods that increase risks from geomorphic change

In flood management terms, flooding is usually defined by the excess water above the capacity of the channel and/or associated flood protection infrastructure. It is attributed a discharge magnitude and annual exceedance probability (AEP in %). Typically, flooding is operationally defined in terms of damage to property or infrastructure or by area of inundation, and can be assigned a risk value for insurance purposes based on exposure and vulnerability of existing assets. None of these terms includes any explicit measure of geomorphic change despite clear evidence of its costs in terms of damaged bridges, flood protection infrastructure, property and land loss/impacts (Environment Agency 2018).

Acreman (1989) reviewed the observed maximum flood peaks and probable maximum floods (PMF) generated by UK catchments, noting that PMF had been attained or exceeded in smaller catchments. Newson (1989) reviewed the observed geomorphologically effective floods and compared these to the Acreman data, identifying that smaller steeper catchments (<10 km^2) were particularly sensitive to convective rainstorms that created high Q_{peak}:Area ratios that corresponded with geomorphic changes. Sear and others (2000) updated the Newson (1989) and Acreman (1989) assessments for the millennium floods of 2000 to 2001.

For this project, Southampton University updated the analysis up to 2019, using data from CEH annual hydrological reviews, published and observed data following the 2009 and 2015 floods, and air photography (Google Earth 2019). Figure 1 and Table 1 summarise the data.

Combining this data shows that:

i. the scale of change during large floods increases with unit discharge (m^{3}s^{-1}km^{-2}). For example, in Northumbria, Milan (2012) reports limited geomorphic adjustment in Knar Burn (1.1 m^{3}s^{-1}km^{-2}) and Glen Burn (1.1 m^{3}s^{-1}km^{-2}), but extensive changes in Thinhope Burn (5.5 m^{3}s^{-1}km^{-2}). Similarly, Carling (1986) reports large scale changes at specific discharges of 2.7 m^{3}s^{-1}km^{-2}), and Harvey (1991) reported major slope failures in the Howgill Fells at 2.4 to 10 m^{3}s^{-1}km^{-2}

ii. in Europe, extensive channel and slope adjustments were reported by Comiti and others (2015) for specific discharges between 12.8-23.7 m^{3}s^{-1}km^{-2}. In contrast, Magilligan and others (1992) report only localised flood plain adjustments in the Galena River at specific discharges of 1.13 m^{3}s^{-1}km^{-2}, highlighting the importance of local factors in controlling flood effectiveness. In the Galena River example, unconfined flood plain allowed flood flows to dissipate energy, creating less erosion and therefore producing less sediment

iii. For UK rivers, the value of unit peak discharge (Q_{peak}) of 1.0 m^{3}s^{-1}km^{-2} marks a threshold above which geomorphic change is likely in most types of channel. This threshold appears to be the same for all sizes of catchment up to around 4,000 km^2, after which Q_{peak} declines because of flood attenuation

iv. on this basis, it is possible to estimate the peak discharge above which geomorphic change is likely based solely on catchment area. For example, during the extreme floods in Cumbria in 2009 and 2015, the geomorphologically effective flood based on the 1:1 threshold can be estimated at >363 m^{3}s^{-1} for the River Derwent at Ouse Bridge gauging station (75003), and >700 m^{3}s^{-1} at the Camerton gauging station

(75002). These values were equalled or exceeded during these floods and that resulted in extensive geomorphic change

This analysis has identified an empirical definition of the geomorphologically extreme flood in UK rivers as that for which unit discharge is >/= 1.0 $m^3s^{-1}km^{-2}$, with large geomorphic changes increasingly likely as unit discharges increase. The emphasis on high unit discharges differs from flood peak based assessments in which magnitude relative to other flows defines the definition of rare events. A geomorphologically effective discharge frequency analysis may generate a specific probability that is skewed towards extreme flows. Such analysis is outside the scope of this report, other than to say that these floods tend to be of low probability <1% AEP.

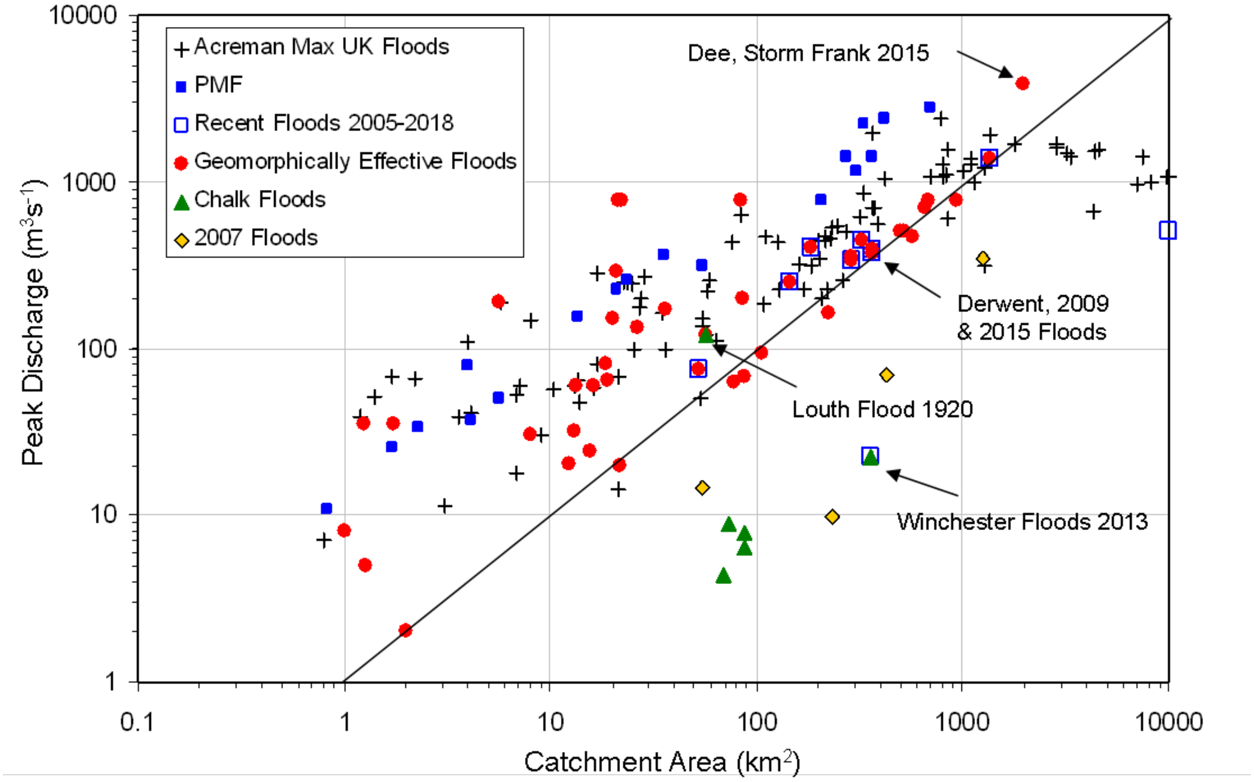


Figure 1 Major UK floods and probable maximum flood estimates showing those known to have experienced major geomorphic change highlighted in red

Geomorphologically effective floods occur for all catchment sizes above a 1:1 threshold, where peak discharges (Qpeak) are larger than the catchment area in km^2 (solid black line) – unit discharge 1.0 m3s-1km-2. Larger catchments > 4,000 km^2 tend not to produce flood peaks that cross this threshold and since channel gradients are typically low, they do not generate the stream powers required to modify their bank and bed materials, transferring instead fine sediments from the catchment surface. Similarly, groundwater dominated chalk streams do not tend to generate the flood peaks necessary for geomorphological change. The exception was the Louth Flood of 1920, when intense rain fell on a chalk catchment with frozen snow cover. The lowland floods of 2007 (Severn at Tewkesbury) are characterised by a low Qpeak/area ratio and had limited geomorphological adjustment except where local factors focused flow or fine sediments were deposited in berms or over flood plains.

2.2 Controls on geomorphic adjustment during extreme floods

The impact of extreme floods on river and flood plain geomorphology is conceptualised under 2 basic theories:

i. magnitude and frequency theory where geomorphic work is quantified by sediment load

ii. flood effectiveness theory in which the measure is of the scale of change occurring in a flood (Hooke 2015)

In effect, both are related by the quantity of sediment transported, and in practice flood effectiveness is most frequently used because it is easier to measure net geomorphic change (channel widening, volumetric changes) than it is to measure sediment load. In terms of river management, flood effectiveness is the most relevant measure as it is most closely linked to damage. However, it is worth remembering that the dimensions and geometry of alluvial (self-formed) channels adjust to fluvial processes operating over a range of flows with low to moderate return periods (Knighton, 1998, Richards, 1999).

It is generally accepted that the dominant or channel forming flow for a dynamically stable channel is similar to the bankfull discharge and has a return interval of between 1 to 3 years in the annual maximum series (Thorne and others, 1999). However, wide variations occur in nature and the return period alone does not provide an adequate basis on which to define the channel forming flow, particularly in more natural conditions where biological processes strongly influence channel form (Castro and Thorne 2019, Thorne and others, 1999). Nevertheless, extreme events of high magnitude but long return period have significant and lasting impacts. They alter channel form and flood plain topography directly through morphological change or through changes to sediment supply via coupling of sources from hillsides to the channel that may influence channel processes for decades afterwards (Harvey 2007). This report focuses on geomorphological effectiveness as measured by deposition and erosion area and/or volume following extreme (>0.2% AEP) floods.

Reviews of published research on flood effectiveness reveal a range of factors influencing geomorphic effectiveness (Table 1). In summary, these include:

i. discharge magnitude (associated with stream power)

ii. stream power and stream power gradient (the downstream change in stream power)

iii. bend curvature through its effect on increasing the shear force on the outer river bank

iv. valley confinement – through its impact on flood power and sediment supply

v. valley constriction and expansion – a specific case of confinement in which high velocity flows rapidly diffuse into a widening flood plain

A series of overseas and UK studies have consistently highlighted the importance of sediment supply, geomorphic adjustment, channel confinement and stream power in controlling the pattern and magnitude of geomorphic change (Harvey, 2007, Surian and others, 2016, Comiti and others, 2015, Drake and Schmidt, 2013).

Sediment supply

Sediment supply provides additional sediment for driving channel change, depending on the power available to transport it. Sediment supply is typically derived from local sources (bed, banks, cliffs, flood plain) when the sediment size is large (gravels or larger), and additionally from wider catchment sources for finer sediments (sands to clays).

Geomorphic adjustment

Geomorphic adjustment has been shown to vary with the extent of channel confinement. Thompson and Croke (2013) differentiate between high (>1,000 Wm^{-2}) stream power confined channel reach responses, and lower power (<500 Wm^{-2}) unconfined reaches. Similar distinctions are made by Surian and others (2016), Rinalidi and others (2015) and Fuller (2008). Broadly, higher power, confined reaches tend to be mostly erosional, with incision and channel widening being the main morphological responses. Infilling of the former channel on the falling stage of the flood is also a recurring observation (Thompson and Croke 2013). Much of the flood plain is stripped or reworked during these events, and slope material is transferred away from source and out of the reach. Hotspots of high stream power and erosion occur in semi-confined reaches at bend apexes where the bend is confined against a terrace or bedrock bluff (Fuller, 2008, Burras and others, 2014).

Valley confinement

Valley confinement is linked both to the coupling of the channel to hillslope sources (sediment supply) as well as influencing specific stream power though its effect on flood width, flow depth and water surface slope during extreme floods (Joyce and others, 2018, Miller, 1995). Confinement can be man-made (from embankments, bridges) or the natural product of geomorphic and geological history (Fryirs and others, 2016). Since natural confinement tends to be maximised in headwater reaches, where valley slopes also tend to be higher, the resulting conditions tend to promote net erosion of the channel, banks and flood plain (Church, 2006, Thompson and Croke, 2013, Riley and others, 2018).

In unconfined reaches, flood waters naturally are distributed across the flood plain, reducing flow depths and stream power. However, where former channels still exist in the flood plain, flood flows may be focused, resulting in local erosion of the flood plain surface or providing weak points in the river bank or embankments.

Man-made changes to flood plains such as buildings, communications networks (roads, railways) or hedge and wall alignments can confine and constrict flood plain flows, resulting in increased stream power and erosional adjustments. In extreme floods, embankments and bridges that cross the flood plain and river channel can constrict the flood waters, leading to excess stream power and channel adjustment.

Stream power

Stream power measures a river’s ability to carry out geomorphic work (transport sediment), and depends on the discharge magnitude, water surface slope and flow width (see Parker and others, 2015 for derivation and definition). Stream power gradient is the rate of change in stream power with distance downstream and can be used to provide an indication of changes in sediment transport capacity with distance downstream (Parker and others, 2015). Lower values of stream power in unconfined reaches are typically net depositional areas, with widening confined to outer banks of meanders where local stream power is focused, or where flood flows are perpendicular to the channel (Magilligan and others, 1998, Burras and others, 2014). Sediments are deposited as wide shallow sand and gravel splays over the flood plain, and benches of fine sediments accumulate on the inside of bends.

Authors	Location	Date	Rain (mm/hr)	Total rain	Geomorphological effectiveness
River channel					
Joyce and others (2018)	St Johns Beck	05/12/15	14.2	341 mm/24 hrs	Flood plain erosion and deposition, boulder transport, landslides, incision, gravel splays, bridge damage
Sear and others (this study)	Scottish Dee	30/12/16	8.3	100 mm/12hrs	Flood plain deposition, channel widening, avulsion, bank erosion, gravel splays, river cliff collapse, bridge collapse and damage
Sear and others (this study)	Kent	05/12/15	14.2	341 mm/24 hrs	Flood plain deposition, channel widening, bank erosion, gravel splays, river cliff collapse, bridge collapse and damage
Sear and others (this study)	Cumbrian Derwent	05/12/15	14.2	341 mm/24 hrs	Flood plain deposition, channel widening, avulsion, bank erosion, gravel splays, river cliff collapse, bridges damaged.
Sear and others (this study)	Cumbrian Derwent	19 to 20/11/09	8.9	213 mm/24hrs	Flood plain deposition, channel widening, avulsion, bank erosion, gravel splays, river cliff collapse, bridge collapse, bridges damaged
Milan (2012)	Thinhope Burn	17/07/07	9.8	236 mm/24hrs	Boulder transport, boulder berm formation, channel widening, bedrock incision, gravel splays, flood plain stripping, activation of river cliffs/confining margins
Sear and others (this study)	Caldew/Eden/Derwent	07/01/05	8.4	200.8 mm 24 hrs	Bank erosion, deposition, flood plain deposition fines
Archer and others (2007)	S.Tyne	07/01/05	9.8	236 mm/24hrs	Bank erosion, deposition, channel change
Sear (1994)	Shelf Brook Glossop	18/06/30 29/05/44	55.3	n/a 166 mm in 3 hrs	Bog bursts, landslides, boulder dumps, bedrock incision, gravel deposition in town, channel metamorphosis
Miller (1951)	North/Mid Wales	29/05/44	36.0	54 mm in 1.5 hrs	Stone deltas
Scott (1950) Basier (1949)	Border/Scotland	12/08/48	4.9	39 mm in 8 hrs	Inner bank deposition, channel change, gravel splays, Bank erosion
Sear (1994)	N. Lake District	10/08/52		n.a.	Destruction of gravel traps, massive bed load transport
Sear (1994)	N. Lake District	15/07/54		n.a	Destruction of gravel traps, massive bed load transport
Arkell (1955)	Weymouth area	18/07/55	37.2	279 mm in 6 to 9 hrs	Gullying bank erosion one landslip
Bleaksdale (1957)	Camelford	08/06/57	55.2	138 mm in 2.5 hrs	Bridges damaged - scouring
Barnes and Porter (1958)	West Derbyshire	06/08/57	30.0	150 mm in 5 hrs	Bridges damaged, scouring and over bank deposition
Duckworth (1969)	Forest of Bowland	08/08/67	78.0	117 mm in 1.5 hrs	Channel sector and deposition (some landslides)
Hanwell and Newson (1970)	Mendip	10/07/68	50.5	101 mm in 2 hrs	Channel, cave and dry valley incision
Valley side slopes					
Johnson and Warburton (2002)	Grains beck	1995	6.8	164 mm/24 hrs	Landslides, debris flows
Hudleston (1930)	Stanmore	18/06/30	12.0	60 mm in afternoon	Deep peat scarred over boulder clay pearly water released
Mitchell (1936)	Co Clare	28/10/34	0.5	85 mm in a week	Slow failure of deep peat with release of semi peat-hag
Hemingway and Sledge (1943) Common (1953)	North York Moors	12/08/38	15.3	46 mm in 3 hrs	Deep peat failure - bog burst

Authors	**Location**	**Date**	**Rain (mm/hr)**	**Total rain**	**Geomorphological effectiveness**
Baird and Lews (1956)	Cairngorm	13/08/56	3.6	86 mm/24 hrs	Solifluction tracks some gullying. Over bank deposition and distributary formation
Crap Rawes and Welch (1964)	Upper Teesdale	06/07/63	1.0	25 mm/24 hrs (thunder)	Peat slide
Beven, Lawson and McDonald (1978)	Bilsdale	09 to 11/09/76	3.7	88 mm in 24 hrs	Failure of head of beck followed by gullying-land slide and debris flow
Beven and others (1978)	N. York Moors	09 to 11/09/76	64.5	86 mm 80 min	Landslip debris flow
Tomlinson and Gardiner (1982)	Slieve an Orra Co. Antrim	01/08/80	129.3	97 mm 45min	Bog slides
Newson (1980)	Mid-Wales	15/08/87	16.3	98 mm 360 mins	Channel deposition
Werritty (1980)	Allt Mor, Invernessshire	04/08/78	33.5	33.5 mm 60 mins	Channel change: boulder transport
Werritty (1984)	Dorback Burn, Invernessshire	06/06/80		n.a.	Bank erosion chaotic deposition
Acreman (1984)	Ardessie Burn, Wester Ross	20/09/81	5.8	140 mm/24hrs	Debris flow channel avulsion
Brown (personal communication)	West Allen, Northumberland	17/07/83	16.7	25 mm 90 mins	Scour channel change
Carling (1986a, b 1987)	Noon Hill, Northumberland	17/07/83	42.0	105 mm 150 mins	Peat slides, boulder berms, jams
Harvey (1986) (Wells and Harvey 1987)	Howgill Fells, Cumbria	06/06/82	28.0	70 mm 150 mins	Slides, flows, fans, channel metamorphosis
Werritty unpublished	Caldwell Burn, Dumfriesshire, Hermitage Water, Rozburgshire	13/06/79 25/07/83	90.0 51.2	90 mm 60mins 64 mm 75mins	Small slope failures, scour Many slides and flows, channel metamorphosis
Macklin and Newson (1990)	Swale, Yorkshire Durham	26/03/36	4.9	118 mm/24hrs	Scour chaotic deposition, run-out

Table 1 Updated data on geomorphologically effective floods in the UK based on Newson (1989), Sear and others (2000) and recently published or observed events

Rainfall conditions associated with each event and the characteristics of the geomorphological changes are given. Slope events occur in response to both antecedent conditions in which the slope sediments are saturated and fail during short intense storms (often convective). In contrast, high rates of rainfall (> 100 mm/24hrs) or intense rainfall dominate the channel events. Slope events are characterised by landslides, peat slides and bog bursts with debris flows and boulder transport. Channel adjustments are characterised by activation of confining margins, flood plain reworking and channel adjustments, including avulsions, widening and extensive deposition on flood plains.

Magilligan (1992) demonstrated how the presence of geological confinements locally increase stream power resulting in net erosion, while Miller (1995) showed that this material is transferred downstream by a steepening water surface slope arising from flow expansion and reduction in flood elevation at the transition from confined to unconfined reaches (see Figure 8). The resulting bank erosion at the transition where the channel is perpendicular to flood flows exiting from the confined reach is severe and feeds the generation of channel benches and flood plain splays (Miller, 1995, Thompson and Croke, 2013).

Langhammer (2010) highlights how depositional responses to extreme flooding occur at the transition from channelised to natural channel planforms. In an extensive data set from 531 reaches of the semi-arid Colorado Front range, Yochum and others (2017) found that the type of geomorphic response was linked to magnitude of stream power, stream power gradient and valley confinement, with increasing stream power linked to increasing likelihood of extreme geomorphic changes (for example, channel avulsions and widening) above a threshold of around 900 Wm^{-2}. The semi-arid context of many of these studies is noted since vegetation has less impact in these systems.

Nanson and Croke (1992) provide a classification of flood plains based on stream power, which broadly follows a downstream trend through a river basin. High energy reaches (300 to 1,000 Wm^{-2}) in non-cohesive sediments have coarse, confined or partially confined steep valley floors, with sediments dominated by coarser deposits. Medium-low energy flood plains (10 to 300 Wm^{-2}) in non-cohesive sediments transition from braided to actively meandering channels in partially confined to unconfined flood plains. Sediment deposits are typically comprised of mobile sands and gravels.

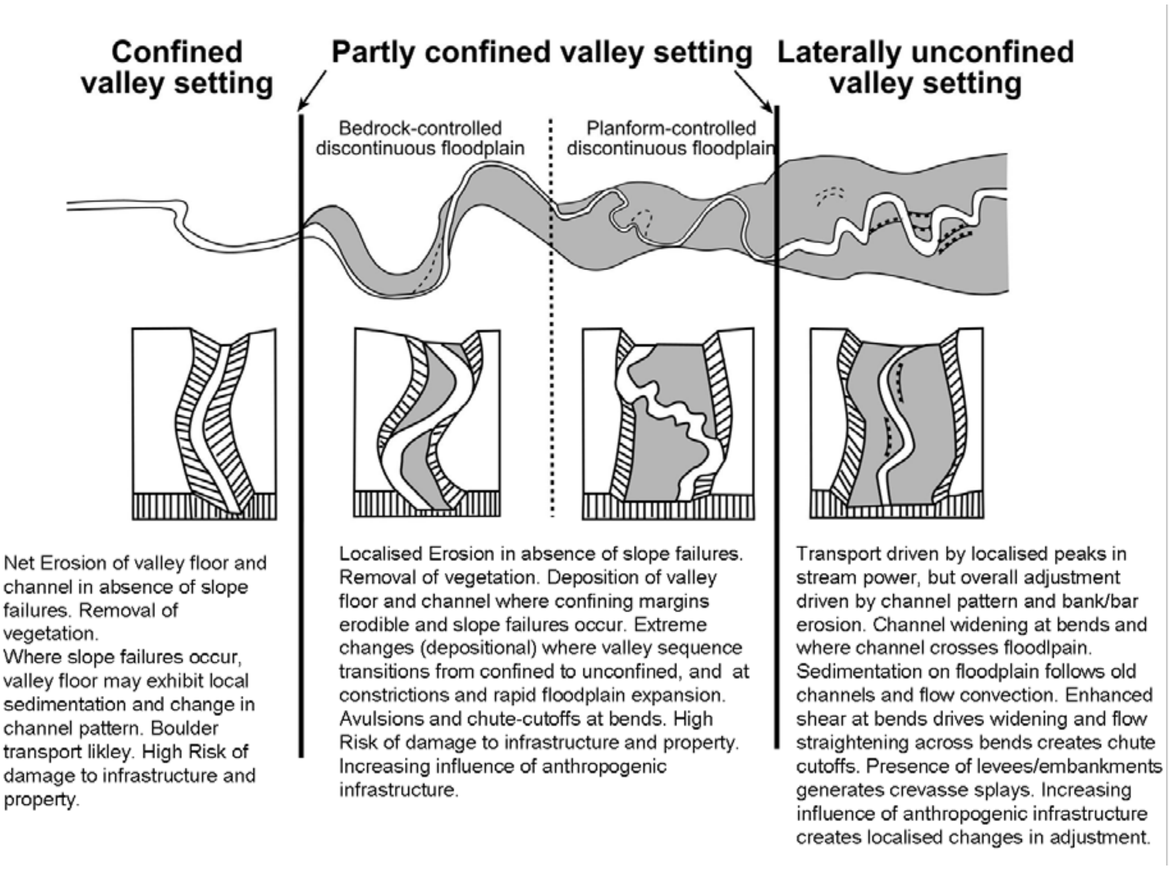
In lowland reaches of larger rivers, cohesive sediments and low stream energy (<10 Wm^{-2}) combine to reduce lateral mobility, while preserving multiple channels. Importantly, these systems are each characterised by different geomorphological responses to flooding. Low stream power (<100 Wm^{-2}) unconfined channels, typical of the lower reaches of larger rivers, have where there is no man-made confinement, strongly diffusive flows, which result in rapid loss of energy at channel to floodplain margins (Knight and Shiono, 1996). However, Brown and others (2001) show how a large lowland gravel bed river adjusted to floods through changing channel pattern, initially widening and avulsing to transform from a wandering to braiding planform, and then subsequently incising during later floods, to develop an anastomosing pattern.

Depositional signatures of extreme floods in lowland flood plain channels are controlled by confinement (levees or embankments), in which overtopping of embankments and levees generate rapid local incision and the formation of crevasse splays (Magilligan, 1998, Middlekoop and Asselmann, 1998). Head-cutting can also occur across lowland flood plains on the falling limb of floods, where return flows develop locally high-water surface slopes between the water on the flood plain (often ponded by levees, embankments) and the channel. Finally, lowland flood plains are typically intensively farmed or modified, increasing risk and damage, but also altering the flow patterns and the spatial distribution of erosion and deposition (Middlekoop and Asselmann, 1998).

Table 1 documents the types of geomorphic change associated with UK geomorphologically effective floods. The majority are confined or partially confined upland steep gradient channels, which are particularly sensitive to high magnitude geomorphic adjustment due to the availability of coarse sediment supply and high stream power.

2.3 Types of geomorphic adjustment in extreme floods – the role of confinement

Valley confinement is a strong control on flood effectiveness. The measure of confinement outlined below results in 2 main transitions (Figure 2): Confined to partially confined reaches, and partially confined to unconfined. In confined reaches, flood flows are confined by valley margins and the whole flood plain/channel is potentially susceptible to erosional adjustments. In addition, confined reaches are strongly linked to sediment sources on the valley sides. Partially confined reaches are sensitive to geomorphic changes. This is because the confined, transport dominated reaches have valley side sediment sources that are then followed by rapid flood expansion into unconfined reaches that have lower stream power and deposition. Unconfined reaches typically have lower stream power due to flow expansion and diffusion out onto shallow flood plain flows. Transport capacity tends to be mostly depositional, with erosion focused on meander bends and where levees and embankments are breached.



Net Erosion of valley floor and channel in absence of slope failures. Removal of vegetation.
Where slope failures occur, valley floor may exhibit local sedimentation and change in channel pattern. Boulder transport likley. High Risk of damage to infrastructure and property.

Localised Erosion in absence of slope failures. Removal of vegetation. Deposition of valley floor and channel where confining margins erodible and slope failures occur. Extreme changes (depositional) where valley sequence transitions from confined to unconfined, and at constrictions and rapid floodplain expansion. Avulsions and chute-cutoffs at bends. High Risk of damage to infrastructure and property. Increasing influence of anthropogenic infrastructure.

Transport driven by localised peaks in stream power, but overall adjustment driven by channel pattern and bank/bar erosion. Channel widening at bends and where channel crosses floodlpain. Sedimentation on floodplain follows old channels and flow convection. Enhanced shear at bends drives widening and flow straightening across bends creates chute cutoffs. Presence of levees/embankments generates crevasse splays. Increasing influence of anthropogenic infrastructure creates localised changes in adjustment.

Figure 2 Relationship between types of valley confinement and the geomorphological effectiveness of extreme floods after Fryirs and others (2016)

> *These reflect natural channel confinement. In reality, man-made confinement through infrastructure and flood protection can cause local increases in confinement, leading to changes in geomorphic effectiveness.*

The distinction between types of confinement sees the influence of confining margins increasingly switching to the influence of stream power, channel sinuosity, channel pattern and the topographic influences of the flood plain on overbank flood depths. Therefore, we might expect the influences of geomorphic change to vary with distance downstream for 4 main reasons:

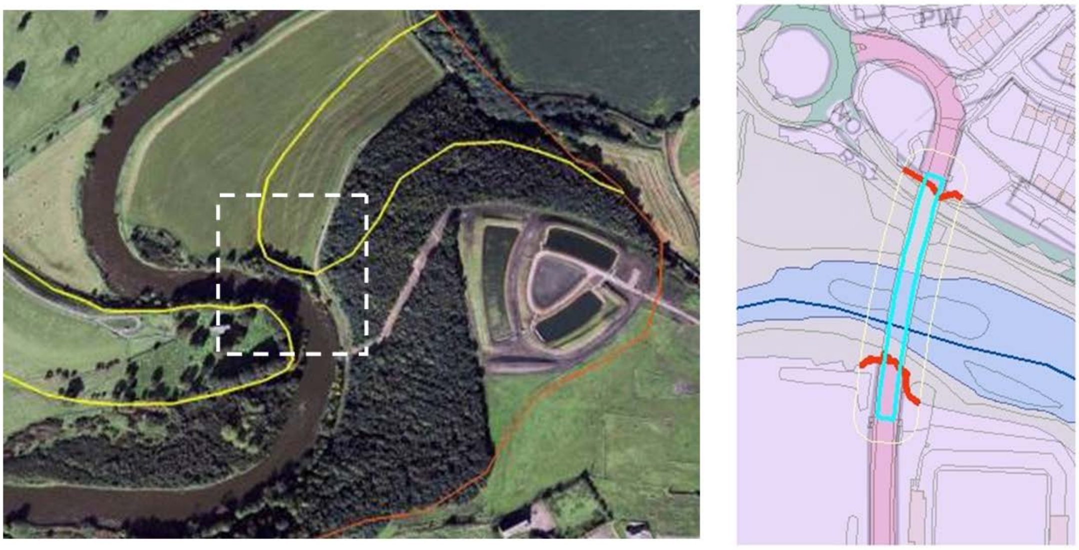
1. Stream power varies with distance because discharge and slope vary along the river network, meaning the ability to transport the sediment load and size range available varies.
2. Shear stress (force acting on the bed and banks) is increasingly influenced by bend curvature and overbank flow paths as confining margins decrease. This element is only really represented in 2D flood model outputs.
3. Sediment supply from confining margins reduces as confinement declines.
4. Sediment supply and stream power change rapidly with tributary inputs, but we assume the channel has adjusted to convey the additional load.

An important variable therefore is the definition of confinement. Here, we refer to the recent review and definition papers of Fryirs and others (2016), Fryirs and Brierley (2018) and O'Brien and others (in review).

Bedrock and alluvial rivers define end-members of a range of channels with different geomorphic diversity (O'Brien and others, 2019). All rivers are influenced by confinement, which determines the space that is available for a channel to adjust on the valley bottom (see Fryirs and Brierley, 2010, Fryirs and others, 2016). Fryirs and others, 2016) defined confinement as the percentage of length of a channel margin that abuts a confining margin (including valley margin, valley bottom margin and man-made margin) on either bank using Equation 1.

$$C_{VB} = \left(\sum_{DS}^{US} CL_{EB} @ C_M \Big/ CL_T \right) \times 100 \tag{1}$$

Where C is confinement; $CL_{EB}@CM$ is the length of channel along either bank that abuts a confining margin ($@CM$) (or valley or man-made margin) and CL_T is total length of channel.



Constriction due to Natural processes (e.g. Glacial features constrict the channel and floodplain flows).

Constriction due to Human modification (e.g. Road bridge).

Figure 3 Examples of flood plain constrictions due to natural geomorphological processes

Constriction due to natural processes (left image): yellow lines are confining margins, with left-hand margin a glacial deposit. White box right hand margin is mine spoil (human modification to the flood plain).

Constriction due to human modification (right image): shows bridge embankments across a river. Constrictions arise when confining margins occur on both sides of a channel at the same reach. Extreme examples are gorges. © Crown copyright and database rights 2019 Ordnance Survey (100025252).

Fryirs and others (2016) and Fryirs and Brierley (2018) distinguish channels on the basis of 4 thresholds (Figure 2; Table 2):

- thresholds, confined (>85% confinement)
- partially confined margin controlled (50 to 85%)
- partially controlled planform confined (10 to 50%)
- unconfined (<10%)

They subsequently differentiate the confinement in terms of the type of confining margin, which, in practice, distinguishes between margins that are erodible and could provide sediment into the current river channel and those that are non-erodible. A specific type of confinement - man-made confinement - distinguishes additional confining margins built by past or current river management, which may be erodible (for example, embankments) or designed to be non-erodible (sheet piling, block stone). In some instances, where they pose a threat of erosion and sediment input, naturally-confining margins can also be confined by structural measures designed to reinforce the confining margin (Figure 3).

Table 2 Definitions of confining margins from Fryirs and others (2016)

Type of margin	**Definitions and identification**
Confining margin (C_M)	Any section of channel margin (either side) that abuts against a valley bottom margin (for natural settings) and/or human margins (for human-impacted settings). The confining margin is not defined by what provides the confinement (for example, levee versus bedrock, valley wall), but instead by what the channel is currently abutting against.
Valley margin (C_{VB})	The valley margin comprises the valley bottom (defined later) and the inactive flood plain (terraces) and fans (both alluvial and colluvial). The valley margin is defined at the transition between the valley floor and bedrock hillslopes. This includes not just bedrock outcrops, but also regolith and soils derived from non-alluvial sources.
Man-made margin (C_A)	The valley bottom comprises the channel and contemporary (active, generic) flood plain. The valley bottom margin separates the valley bottom landforms from other valley floor landforms (for example, fans and terraces) and hillslope landforms. Confined, partly confined and laterally unconfined valley settings are defined by the extent of the valley bottom margin (Brierley and Fryirs, 2005). The width between opposite valley bottom margins is referred to as the effective valley width (Fryirs and Brierley, 2010).
Channel margin (CL_{EB})	The channel margin is the edge of the active channel (in many systems this corresponds with the bankfull margin). The channel margin is the boundary between where regular fluvial flows take place and other areas (for example, flood plains where less frequent flows take place; terraces, where historic fluvial flows took place; hillslopes where fluvial flows do not take place).

In addition to confining margins, a particular type of confinement, known as ‘a constriction’ is when both sides of the river abut confining margins. Constrictions are important in terms of geomorphic landscapes and flood effectiveness since they define natural gorges but are also characteristics of human modified reaches where embankments and bridge abutments extend across the flood plain constricting the channel, or where embankments confine the channel on both banks. Fryirs and others (2016) define constriction using Equation 2:

$$c_P = \left(\sum_{DS}^{US} CL_{BB} @ C_M \Big/ CL_T \right) \times 100 \qquad (2)$$

Where $CL_{BB}@C_M$ is the length of channel that is confined along both banks.

Confinement and constriction are measures that can change over time in partial and unconfined reaches as the river migrates away or into a confining margin, or extends or contracts along an existing confining margin. Similarly, planning decisions can result in an increase or decrease in confinement and constriction over time, with potential impacts on flood effectiveness.

In the River Derwent, Cumbria, a range of examples of human confinement and constriction resulting mainly from building railway and road embankments and bridge crossings along the valley floor (Figures 4 to 7) influenced geomorphic change. In urban areas, constrictions and confining margins are often protected, meaning that geomorphic changes can be lower than expected, although undermining of banks due to bed scour are also common in these circumstances (Figure 5).

Figure 4 Examples of 3 sources of human activity that affect confinement and constriction during an extreme flood – Papcastle, Cumbrian Derwent

The extreme floods of 2009 and 2015 are constricted through the bridge and embankments, which resulted in increased stream power and extensive bed and bank erosion (visible on the left of the channel).

Figure 5 Example of urban confinement and, in the distance, constriction where development and flood protection walls along the River Cocker resulted in high stream power

> *In this instance, the banks are protected, and sediment transport was limited by a lack of local supply from bank erosion and the armoured sediments on the bed.*

Figure 6 Example of a valley constriction created by a disused railway embankment crossing the flood plain and River Derwent downstream of Camerton

> *Flood waters and sediments were forced through a narrow section where the former bridge crossed the river, followed by rapid expansion. The increased power through the constriction scoured bed and banks immediately downstream*

> *but the expansion ultimately reduced power rapidly and forced deposition across the flood plain and in the river channel (view looking down valley).*

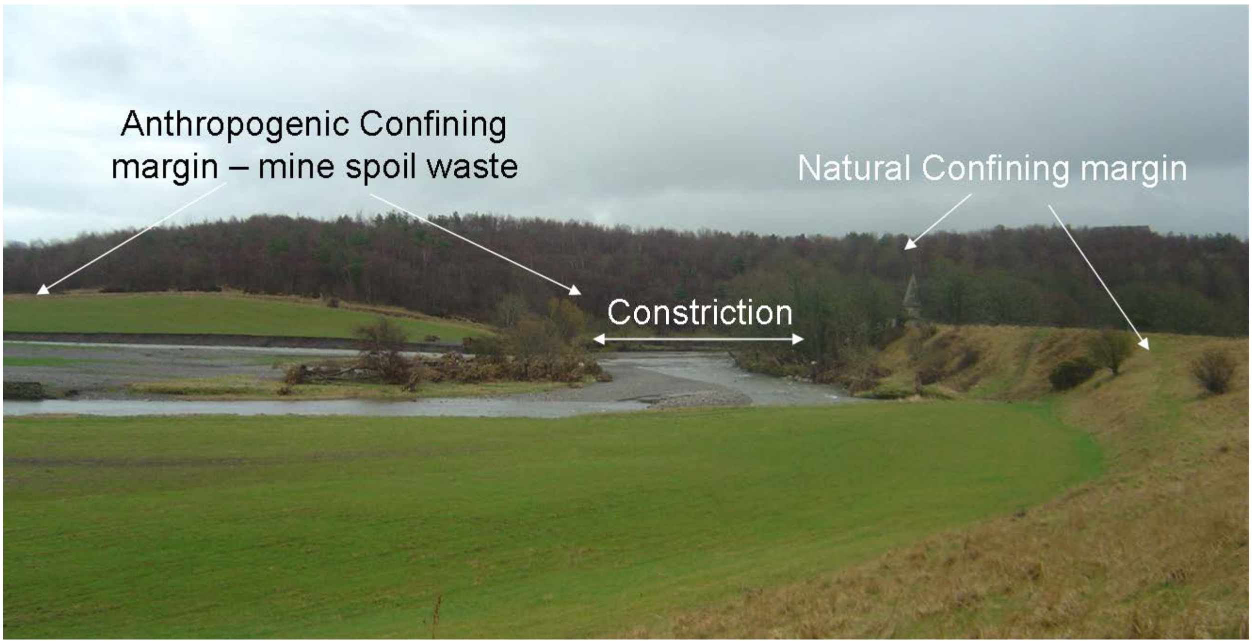


Figure 7 Example of a natural confining margin together with a man-made confining margin from mine spoil creating a constriction at Camerton, River Derwent

> *A whole portion of the valley and river were buried under mine spoil forcing the river to flow through a narrow constriction, generating high stream powers and erosion of the bed and banks. View upstream of Figure 6 above.*

Confining margins are important sources of sediment (where erodible), and the location where flood flows are influenced by the topography. Miller (1995) demonstrated, through 2D hydraulic modelling, the impact that constrictions and confinement had on flood hydraulics. Expansion of the flood plain reduces flood elevation at the transition from confined to unconfined reaches, locally increasing water surface slope and elevating shear stress. Figure 8 illustrates the impact of expansions immediately downstream of a constricted reach on local shear stress (a measure of force on the bed and banks driven by water surface slope and flow depth) and flow direction.

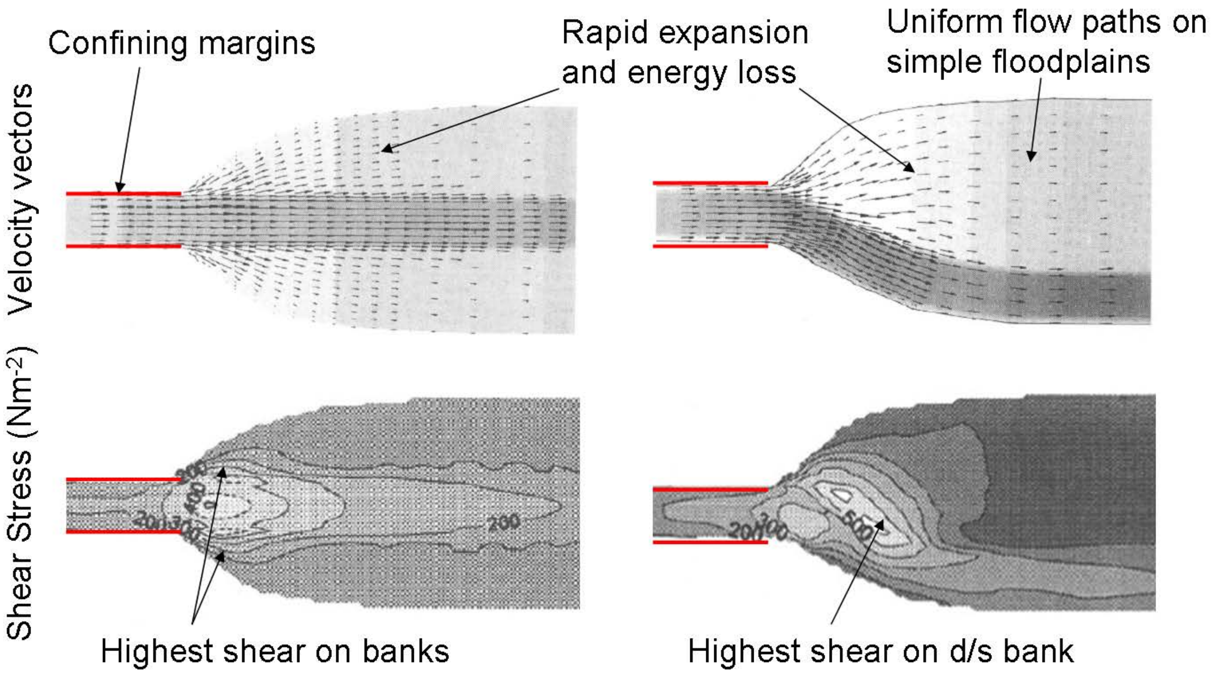


Figure 8 Modelled effects of constriction followed by expansion of the flood plain on a straight channel alignment (left) and on a curved channel alignment (right)

> *Highest shear stress occurs just downstream of the expansion and on the downstream bank in the curved channel. These would be locations of bed and bank erosion. Expansion of flows results in rapid reduction in shear stress downstream and on the flood plain, which would be characterised by channel and flood plain deposition of sediments eroded at the constriction/expansion transition. After Miller (1995).*

The sequence of confinement and the relative curvature of the channel appear to be important factors influencing the hydraulics that generate geomorphic effectiveness. It is therefore the spatial arrangement of confining margins, constrictions and expansions that are important for understanding the location of geomorphic change.

Figures 9 shows a case study from the River Derwent at Papcastle. The effect of the road crossing is to constrict the flows. Erosion and deposition occur within and downstream of the constriction as predicted in the Miller (1995) model. Rapid expansion of flows downstream as the channel turns right (north) reduces stream power and results in massive deposition on the flood plain. The fact that the same sequence of erosion and deposition occurred in 2015 during Storm Desmond at this site highlights that the pattern of confinement and constriction sets up the flood hydraulics template that interacts with the erodible margins to drive the patterns and magnitude of geomorphic change. This physically based assessment suggests that it may be possible to determine indicators of stream power and confining margins to predict geomorphic change during extreme flooding.

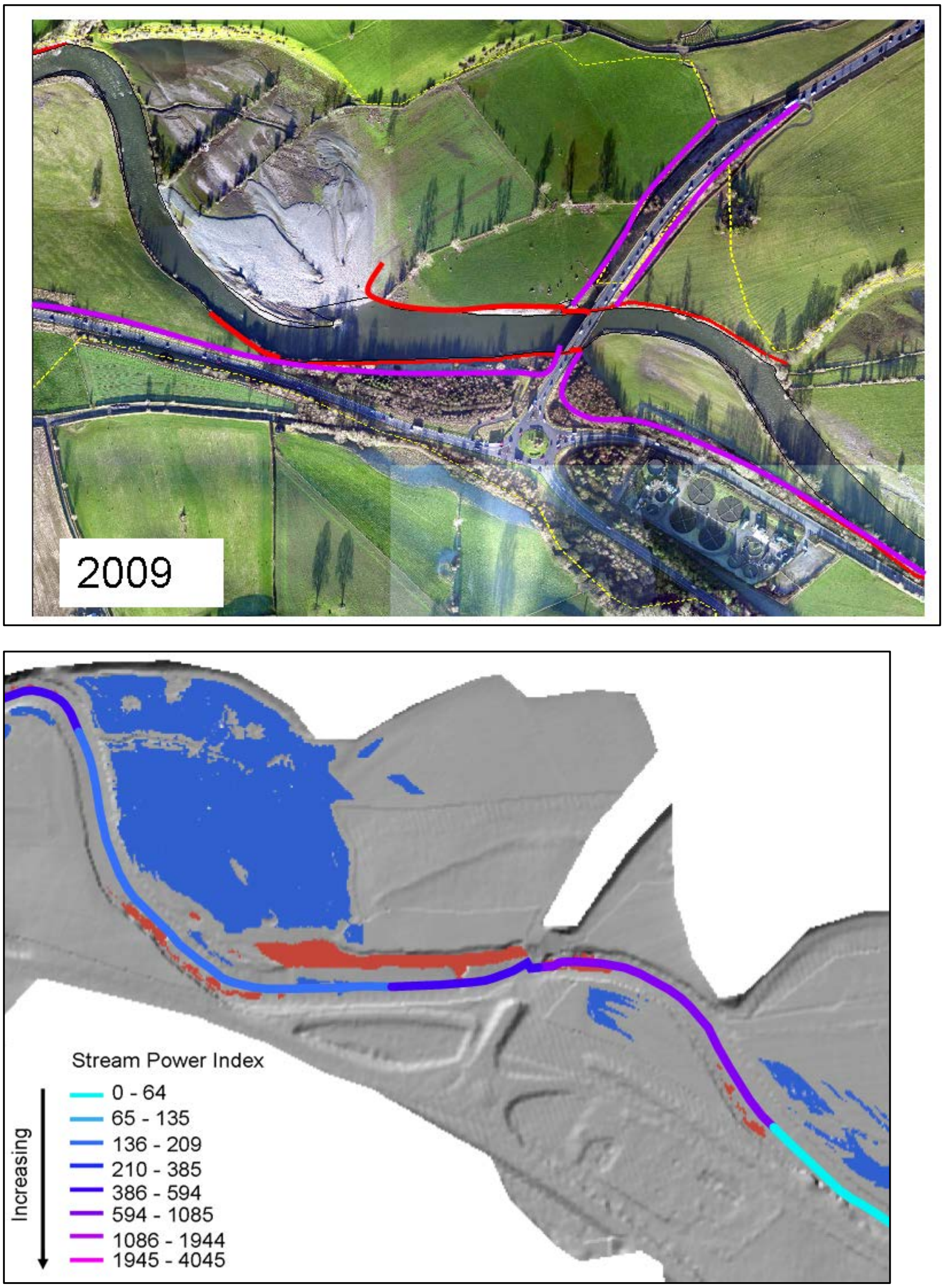


Figure 9 Confinement and constriction through a road bridge and the resulting patterns of stream power and geomorphic change. Papcastle, Cumbrian Derwent floods of 2009

Flood flow is from right to left. Red lines in the upper figure are protected margins, purple lines are man-made confining margins and yellow dashed lines are natural confining margins. In the lower figure, the areas of erosion are marked in red, flood plain deposition in blue.

3 Methods

3.1 Summary

The methods adopted in this report were based on 3 concepts:

i. availability of a data rich case study (River Derwent, Cumbria) for the 2009 Cumbrian floods that had highlighted the potential importance of confinement on predicting geomorphic response to extreme floods

ii. review of the literature to expand the evidence for specific influences of geomorphic change during extreme floods and to confirm that the observations from the case study site (i) were generic

iii. development of additional case studies to develop and test conceptual or statistical models and provide evidence to apply them to other river systems

Together, these provide a framework for the subsequent results and data analysis.

3.2 Quantifying risk of geomorphic change during extreme floods

3.2.1 Approach

The approach for quantifying risk of geomorphic change during extreme floods is based on determining potential physical factors that are found throughout the academic literature.

This included:

i. defining the potential factors influencing reach-scale geomorphic change

ii. determining suitable measures for these factors using nationally applicable data sets

iii. using statistical analysis, where possible, to identify which factors best predict geomorphic change in a) Derwent and b) geomorphic change data

iv. using multi-criteria assessment (MCA) approaches to score reaches at risk of geomorphic change and mark against the 2 Derwent geomorphic change data sets

v. testing resulting MCA scores against an independent data set (Kent fluvial audit) of geomorphic change

vi. converting risk of geomorphic change into overall risk due to geomorphic change based on intensity of land use

How applicable the data and processes were to national scale development was considered at each step.

3.2.2 Defining the potential factors influencing geomorphic change

Based on the review of academic literature carried out for this study, potential factors of geomorphic change were identified and are summarised in Table 3. These are measures that recur in the literature, are process based, and that are readily estimated from existing spatial data sources, with the potential to be used nationally.

Table 3 Potential process-based predictors of geomorphic change recurrent in the academic literature

Where possible, the project team has used predictors that are not specific to individual case studies or particular, non-UK relevant physiographic and climatic contexts. Details on how to derive these are in the Methods section and Help file.

Influencing factors	Measures required	Relationship to geomorphic change (GC)	Examples
Unit stream power	Q, S, b, catchment area (m^2)	Positive High ω = > GC	Magilligan (1992) Burrass and others (2014) Milan (2012) Joyce and others (2018) Yochum and others (2017)
Bend stress sinuosity	Rc/w $L_{channel}/L_{valley}$	Positive >Rc/w = >bank erosion	Burrass and others (2014) Fuller (2008)
Confinement/ constriction	Confinement proportion	Positive >Cf = > GC	Miller (1995) Joyce and others (2018) Yochum and others (2017)
Flood plain expansion	Downstream/up-stream width ratio	Positive >Exp ration = > deposition change	Miller (1995) Joyce and others (2018)
Confining margin erodibility	BGS drift or solid geology classified into erodibility	Positive >erodibility of confining margin = >GC	Newson (1977)

3.2.3 Data sets of geomorphic change

Geomorphic change data is still relatively rare and typically very site-specific, often involving short reaches (for example, Milan 2012, Wheaton and others, 2010). However, improvements in spatial data collection (for example, LiDAR) and topographic survey coincident with bathymetric surveys and air photography is rapidly changing the ability to capture 2D and 3D data. Alongside these data, researchers have increasingly developed free or commercial products for handling such data sets and deriving a range of useful geomorphic outputs (for example, Wheaton and others, 2010). For this project, the project team used 3 types of geomorphic change data:

- a fully 3D digital elevation model of the River Derwent before and after the 2009 Cumbrian floods, and a DEM of Difference (Wheaton and others, 2010) that estimates the gross and net erosion and deposition volumes. This data was collected as part of NERC Urgency grant GR3/C0018
- digital air photography of the River Derwent flown for the Environment Agency after Storm Desmond in January 2016. We digitised the bank line, bars and flood plain erosion and deposition and converted them to areas of erosion and deposition per segment for the whole Derwent flood plain between Lake Bassenthwaite and Workington – including the same areas as the River Derwent, Cumbria data set
- post Storm Desmond fluvial audit carried out by JBA (JBA 2018). The bank erosion (polylines) and deposition (points) were used from this data set and combined to give a measure of geomorphic change along the Kent flood plain. No before and after LiDAR or air photography was available for this river

In the future, it may be possible to extend this data set using information from the River Dee, Scotland (Wheaton pers comm.) and air photography of other affected rivers (for example, South Tyne, Eden, Caldew).

Three data sets of change for the River Derwent were developed; 2009 volumetric change data per 500 m segment, 2015 area of geomorphic change per 500 m segment, and a combined change area 2009 and area 2015 = total geomorphic change per 500 m segment. These 3 data sets were then used to calibrate and test the statistical and multi-criteria assessment models.

Appendix A shows how the measures for the influencing factors and input data sets were derived. Figure A1 provides an overview of the workflow for processing, calculation and risk mapping.

Working out the risk of geomorphic change involved segmenting the network, calculating confinement-related measures, and confining margins and then attaching this resulting data back to the segments. This was so that confinement could be mapped, MCA scores computed and risk due to geomorphic change based on intensity of land use identified. The data and spatial processing steps are illustrated in Figure A1. Table A3 provides an overview of the main steps for generating the intermediate spatial data sets and subsequent measures, which are then joined back to the river segment. This processing uses the Riverscapes Confinement Tool to process confining margins data and the Geomorphic Network Analysis Tool (GNAT) to process river networks.

3.3 Sediment supply

The supply of sediment available to a given 500 m reach of channel is a product of the bed, bank and valley side material plus any tributary input to a reach. In practice, the main source of sediment in extreme flooding is erosion of confining margins where that material is erodible. An important distinction arises between confining margins that are erodible (for example, sands, gravels, cobbles) and those that are not (for example, clay till, bedrock). The supply from confining margins also relates to the area of erodible material, which, in turn, relates to the length and height of the confining margin. Since we will not know until after an event what the erosion distance is into the confining margin we do not convert to a volume, choosing instead to scale sediment supply by the area of erodible confining margin in a reach plus that in the upstream reach (based on an assumption of sediment transport distance – see below).

3.3.1 Defining sediment supply connectivity during extreme floods

To estimate the likely extent of upstream sediment supply to a reach we need to know how far gravel particles travel during extreme floods. Data on the distances travelled by gravel are largely derived from empirical field measurements and are relatively rare. Hassan and others (1992) provide an estimate of mean gravel transport distance as a function of excess specific stream power above the critical power required to entrain a gravel particle of a diameter (D_i):

$$L_m = 0.0283(\omega - \omega_c)^{1.44} \qquad (1)$$

Where L_m is the mean travel distance for a gravel particle of diameter D_i, ω is the specific stream power of a reach, and ω_c is the critical specific stream power for a particle of Di. Specific power is given by the formula:

$$\omega = \gamma QS/b \qquad (2)$$

Where γ is the specific mass of water (density x gravitational acceleration), Q is the peak discharge in cumecs, S is the water surface slope and b is the channel width. Critical stream power ω_c was estimated from an empirical model developed by (Petit and others, 2005), based on published field estimates from gravel bed streams:

$$\omega_c = 0.130 D_i^{1.44} \qquad (3)$$

We calculated L_m for the 16th, 50th and 84th percentiles of grain size data from flood plain and channel flood deposits and modelled specific stream power from the River Derwent following the Cumbrian floods in 2009 (Wong and others, 2015). These values were then used to derive an average length of travel for 100 m segments along the River Derwent. For flood plain deposits, L_m was ~608 m, while for the coarser channel deposits the value of L_m was ~596 m. We concluded from this analysis that sediments in a given 500 m reach were connected to the upstream 500 m reach during the kinds of extreme floods experienced in 2009 and 2015. While it is possible to modify the connectivity values for each reach by the stream power of that reach, in reality that data may not be available for every river, and the grain size distribution for each reach will almost certainly not be available. We therefore assume that sediment supply to a 500 m reach in all instances of extreme flooding is a product of the sources available within that reach plus the upstream reach.

3.3.2 Statistical analysis

To determine which variables were best at predicting the observed geomorphic change the project team attempted a backwards stepwise regression analysis (BSMR). BSMR builds a linear multiple regression model, and sequentially removes the variables that contribute the least to predicting the geomorphic change, resulting in the best combination of predictors. To run BSMR, the predictor variables have to be independent of each other and all data must be normally distributed or transformed to become normally distributed. Of the potential influencing factors many were strongly linked (for example, stream power and expansion ratio correlated negatively because valley width is used to work out both measures). Similarly, all the measures except expansion/contraction ratio were not normally distributed, and for most of these the project team was unable to transform them into a normal distribution. As a result, the team was unable to perform this analysis.

To reduce the number of factors those that were strongly linked were removed. This left stream power gradient, area of sediment supply and sinuosity as potential measures. Sinuosity was not significantly linked with any measure of geomorphic change and was omitted from further analysis. An independent multivariate principal components analysis (PCA) was run on all the influencing factor measures to determine which measures explained the highest proportion of change in the data. PCA analysis showed a leading mode in the data based on stream power gradient and sediment supply, which together accounted for 74% of the total variance in the data. The project team therefore selected these 2 measures as potential influences of geomorphic change. Theoretical considerations support these since stream power gradient is the basis for the ST-REAM model and is theoretically linked to erosion and deposition and therefore geomorphic change (Parker and others, 2015). Area of sediment supply is linked to geomorphic change because it can provide a proxy for the amount of sediment that can be deposited. Stream power is largely a measure of the ability to transport sediment, with the quantity transported being linked to the magnitude of stream power above the threshold for mobilising bed material (Bagnold, 1966), which in extreme floods is almost always exceeded. Since general bed mobility is assumed in extreme floods, stream power gradient is in fact a measure of the rate of change in transport capacity, therefore the project team did not need a separate measure of stream power.

Separate linear correlation between measures of geomorphic change and stream power gradient and area of sediment supply showed that area of geomorphic change was a better predictor. For the subsequent MCA analysis therefore stream power gradient was weighted lower than area of sediment supply.

3.4 Predicting the magnitude and location of geomorphic change

Multi-criteria assessment (MCA) is an approach that can be used in GIS modelling (Sear and others 2009) and allows spatial data to be combined within a framework of scoring and weighting to represent the relative importance of each variable or variable combinations. In the absence of statistical models, this approach is useful for representing the spatial relationship between different measures and is used in decision support systems. It is important to understand that MCA-based decision support systems (DSS) cannot make decisions but can help to inform them. Central to this is to make sure that the information is presented in a format that is not overly-technical (Sear and others, 2009, Clark and Richards, 2002). If the results of decision support systems (DSS) are too technical, they may risk being misinterpreted or may not be useful to those making the decisions.

The project team adopted an MCA approach to predict the magnitude and location of geomorphic change along the River Derwent, Cumbria. Stream power gradient and area of sediment supply were differentially weighted based on their ability to predict the observed geomorphic changes in the River Derwent (2009, 2015, combined change). Stream power gradient was given a weight of 1.0, and area of sediment supply a weight of 2.0.

To develop scores for each predictor, the total range of each predictor was divided into classes using natural breaks, but then repeated until the best fit was obtained against the observed scale of geomorphic change. The project team allocated a score to the resulting classes. For stream power gradient, scores varied according to the magnitude of the gradient in power. Large positive and negative changes in stream power gradient were scored highest. The rationale is that large reductions in stream power (high negative power gradient) are locations of sediment deposition and associated channel widening. Similarly, large increases in stream power are locations of large-scale erosive adjustment. Relatively modest stream power changes are overwhelmed by the availability of sediment supply, therefore lower scores were apportioned to the intermediate classes of power gradient (Table 4).

Table 4 Optimum scoring allocated to stream power classes after iteration against observed geomorphic change on River Derwent 2009, 2015 floods

Power gradient classes (ratio)	Score	Weight
< -850	5	1
- 849 to 500	3	1
-499 to130	1	1
-129 to 230	0	1
231 to 500	1	1
501 to 960	2	1
961 to 1,200	3	1
>1,200	5	1

For area of sediment supply, calibration against observed geomorphic change on the River Derwent resulted in the scores and classes shown in Table 5.

Table 5 Optimum scoring allocated to area of sediment supply classes after iteration against observed geomorphic change on River Derwent 2009, 2015 floods

Area (m^2) sediment supply classes	Score	Weight
0 to 750	1	2
751 to 1,550	2	2
1,551 to 2100	3	2
2101 to 2900	4	2
2901 to 3300	5	2
3301 to 5000	6	2
>5000	7	2

To calculate the final MCA score the following formula is used:

$$\text{MCA Score} = \omega_s + (A_s \times 2) \tag{4}$$

The project team found considerable improvement in predicting the scale of geomorphic change when it applied a 3-point moving average to the MCA score and the detrended value of geomorphic change. The detrending is necessary for the Derwent case study because of the modulating effect of Lake Bassenthwaite on actual stream power. The catchment area-based stream power index does not represent the lake effect, and results in over prediction of stream power and resulting power gradients in the first 15 km downstream. The project team did not apply the detrending to the independent test on the River Kent. In any future analysis the team recommend using a discharge-based value of stream power that would account for storage features such as lakes and reservoirs.

Smoothing the data is justified by the transport distance analysis and is supported by previous studies that found connectivity between reaches explained more of the geomorphic change. For example, Bizzi and Lerner (2013) found that stream power averaged over 3 to 5 km upstream segments was the best predictor of whether a channel was erosional or depositional. Similarly, Gartner and others (2015) found that negative stream power gradient calculated from a moving average with a window ranging from 200 to 1,000 m, corresponded well with erosional responses to floods, and that a positive gradient corresponded well with aggradational responses (Yochum and others, 2017).

The final MCA score is based on a 3-point moving average value and is calibrated to the detrended 3 point smoothed Derwent total geomorphic change (Table 6). Therefore, the actual magnitude of geomorphic change is not being modelled, rather segments of the river and flood plain are allocated to classes of geomorphic change (Table 6). At a national level, this could provide resource managers with a tool to screen for potential 'hotspots' of where geomorphic change is most likely to occur during extreme floods.

Table 6 Final classification of MCA score into class of scale of extreme flood geomorphic change

MCA score 3pt moving average	Magnitude of geomorphic change
< 2.0	Very low
2.1 to 5.0	Low
5.1 to 8.0	Moderate
8.1 to 11.0	High
> 11.0	Very high

The resulting procedure used for deriving the index of geomorphic change is:

i. Calculate stream power gradient using formula

$$\omega_c = \omega_i - \omega_j \tag{5}$$

Where ω_i is specific flood power at a flood plain segment, and ω_j is specific flood power at the upstream flood plain segment.

ii. Calculate area of sediment supply using the formula:

$$A_s = A_i + A_j \tag{6}$$

Where A_i is area of erodible confining margin at a flood plain segment, and A_j is the area of erodible confining margin at the upstream flood plain segment.

iii. Convert values into scores using Tables 4 and 5 and formula (4) above.

iv. Calculate a 3-point moving average, starting at the upstream segment.

v. Reclassify values into magnitude of geomorphic change using values in Table 6.

3.5 Determining risk

Geomorphic change during extreme floods is a natural process. For the purposes of flood risk management, incident response and land use planning it is important to understand where geomorphic change intersects with land use that has high value both to individuals (for example, a home or livelihood) or to society more widely (for example, an electricity power line), as risk is a combination of likelihood and impact (consequences).

For risk assessment, it is therefore assumed that geomorphic change in a woodland or wetland is a lower risk than for an urban area of road or rail line.

To convert the predicted values of geomorphic change into a risk category we used the raster layer of land use intensity (See Help file for details). Those segments with high predicted magnitude of geomorphic change and high land use intensity value (urban area, road/rail network) are high risk reaches. This may help flood risk managers or planners to focus future detailed analysis and mitigation actions (Figure 13).

	Magnitude of geomorphic change				
Land use intensity	**V. Low**	**Low**	**Moderate**	**High**	**V. High**
V. low	**V. Low**	**V. Low**	**V. Low**	**Low**	**Low**
Low	**V. Low**	**Low**	**Low**	**Moderate**	**Moderate**
Moderate	**V. Low**	**Low**	**Moderate**	**High**	**High**
High	**Low**	**Moderate**	**High**	**High**	**V high**

Figure 13 Classification of the risk of geomorphic change during extreme floods based on magnitude of change at a segment and the land use intensity value.

The values assigned to each class of land use intensity are negotiable and could be a starting point in any discussion with interested groups. It would, in practice, be much better to involve interested groups in deriving a flood plain specific weighting for these values.

4 Results

4.1 MCA and geomorphic change: River Derwent case study

Total geomorphic change and the resulting MCA for the River Derwent are presented in Figure 14 together with reaches protected by flood risk management defences. The results for geomorphic change have been detrended to account for the lake effect from Bassenthwaite but are not smoothed. There is positive and significant correlation (Pearson correlation $R = 0.48$, $p < 0.001$, $n = 43$) with the observed total geomorphic change at this stage. Encouragingly, flood protection reduces the actual change below what might be predicted from the MCA in the vicinity of Cockermouth. However, there are notable underestimates between MCA scores and observed changes around the Camerton reach and at 30,000 m downstream (Figure 14). In the latter case, this is a reach where all indicators suggest relatively minor geomorphic change, but the observed change is far larger. This section is characterised by a low sediment supply from confining margins, partially confined and a minor reduction in stream power gradient. The observed changes are characterised by deposition of gravels and sand sheets over the flood plain where the river cuts across the valley centreline and turns abruptly against a protected road embankment and terrace. The difference is explained by the location at which the reach has been automatically cut for the 500 m segment, which, in this case, reduces the available sediment supply and stream power gradient. This highlights an issue common to all segmenting algorithms where these are standardised by reach. In some unspecified cases, the location of where segments have been cut may influence the calculation of the final measures. Resolving these issues within the risk mapping may rely on local knowledge. Alternative approaches segment on the basis of changes in the measures themselves, although they tend to result in very long segments that miss localised variability (for example, Bizzi and Lerner, 2013, Parker and others, 2015).

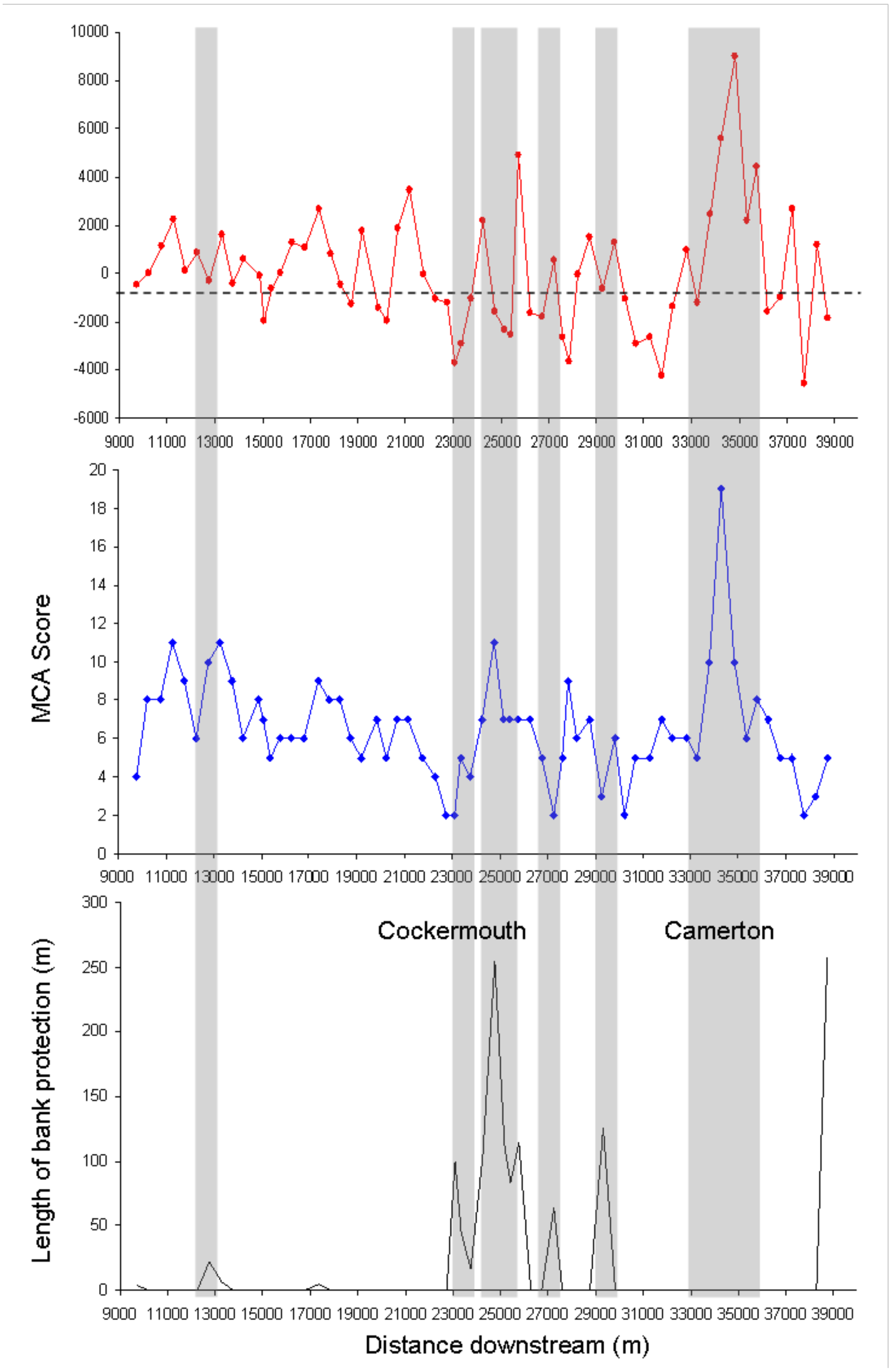


Figure 14 a) Detrended total geomorphic change (2009 and 2015), b) MCA scores and c) Total protected bank length for the River Derwent Bassenthwaite to Workington Weir

> *Linear Pearson correlation between MCA and GC is strongly positive (R = 0.48, p <0.001). Protection works derived from the national flood risk management asset database (grey bands) correspond to the main urban settlement at Cockermouth, and its effect is to reduce actual geomorphic change relative to predicted change.*

Figure 15 shows the same data but smoothed using a 3-point running mean (effectively smoothing over 1,500 m). The correlation between MCA score and observed geomorphic change increases to R = 0.72, which is positive and significant.

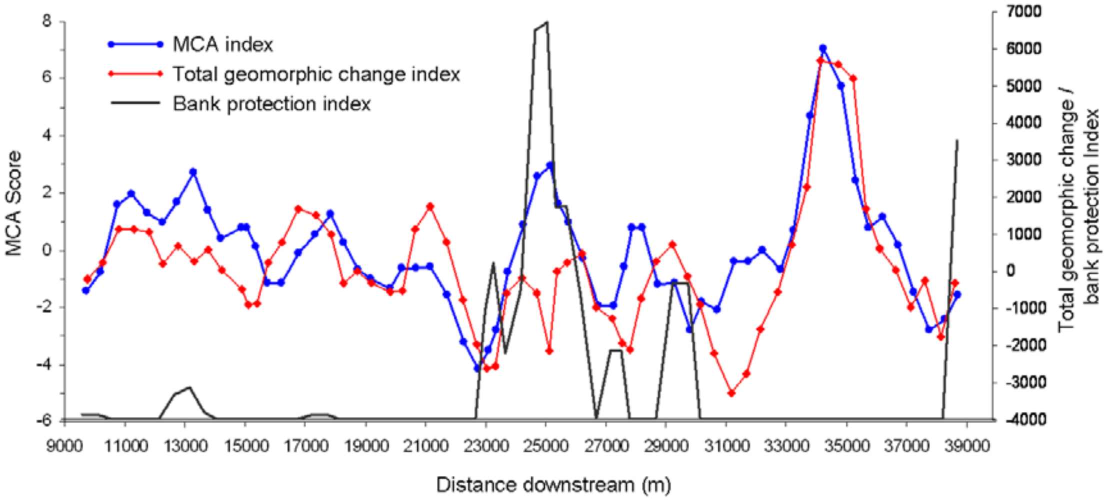


Figure 15 Same as Figure 14 but smoothed using a 3 point (1,500 m) moving average

> *Linear Pearson correlation increases to R = 0.72, p <0.0001. Red is detrended, smoothed total geomorphic change, blue is smoothed MCA, black is smoothed bank protection (values same as in Figure 14).*

The reaches that had any form of bank protection were removed (blacklines in Figure 15), as these are not accounted for in the MCA model. The resulting significant linear model accounted for 52% of the variation in observed geomorphic change (Figure 16). Linear correlation shows it accounts for 74% of observed variation, so this is identifying most of the change in the right location and all of the high change. It has problems overpredicting in the upper reaches due to the lake effect not being accounted for in the stream power measure used, but that could possibly change moving forward. This is similar to published performances from other studies of flood effectiveness (Surian and others, 2016, Bizzi and Lerner, 2015). The project team therefore used this as the basis for generating the MCA categories and geomorphic change classes shown in Figure 17.

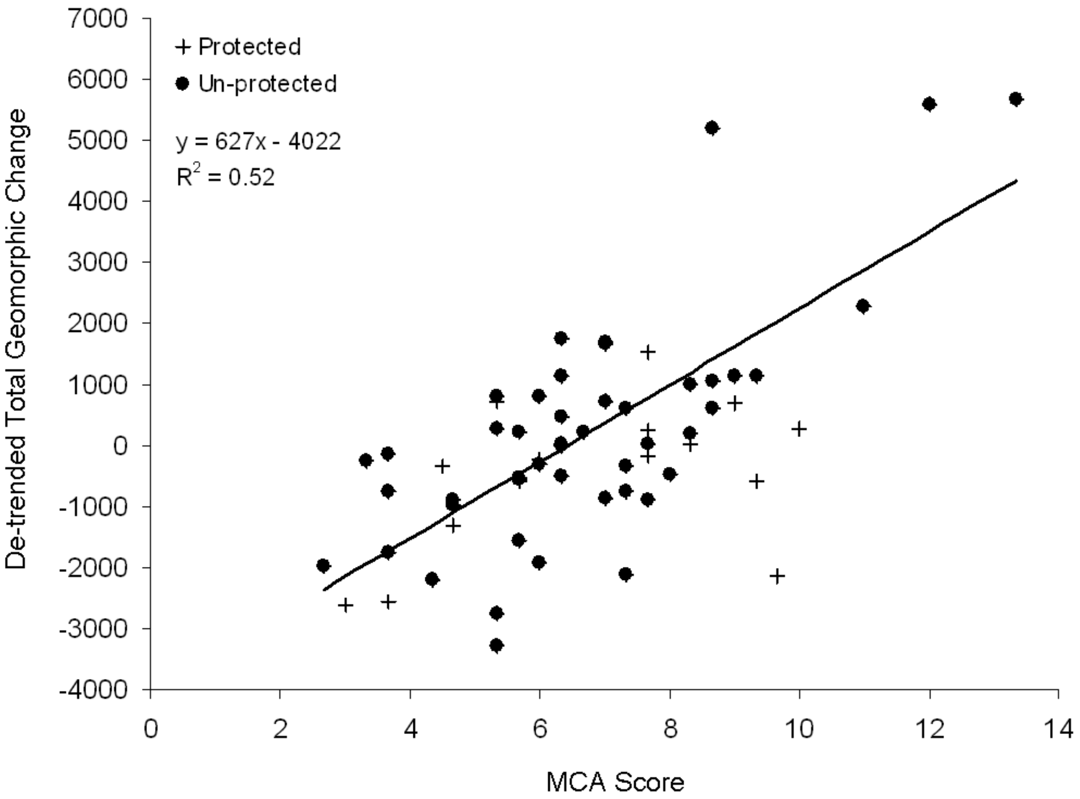


Figure 16 Relationship between smoothed MCA and detrended and smoothed total geomorphic change

Linear least squares regression model provides strongest prediction ($R^2 = 0.52$, $p < 0.001$) when protected reaches are removed. Predicted values are high relative to other published sources (for example, Comiti and others, 2015, Surian and others, 2016), and demonstrates the importance of accounting for sediment supply, stream power gradient and local factors (erosion protection) in determining relative magnitude and location of geomorphic response to extreme flooding.

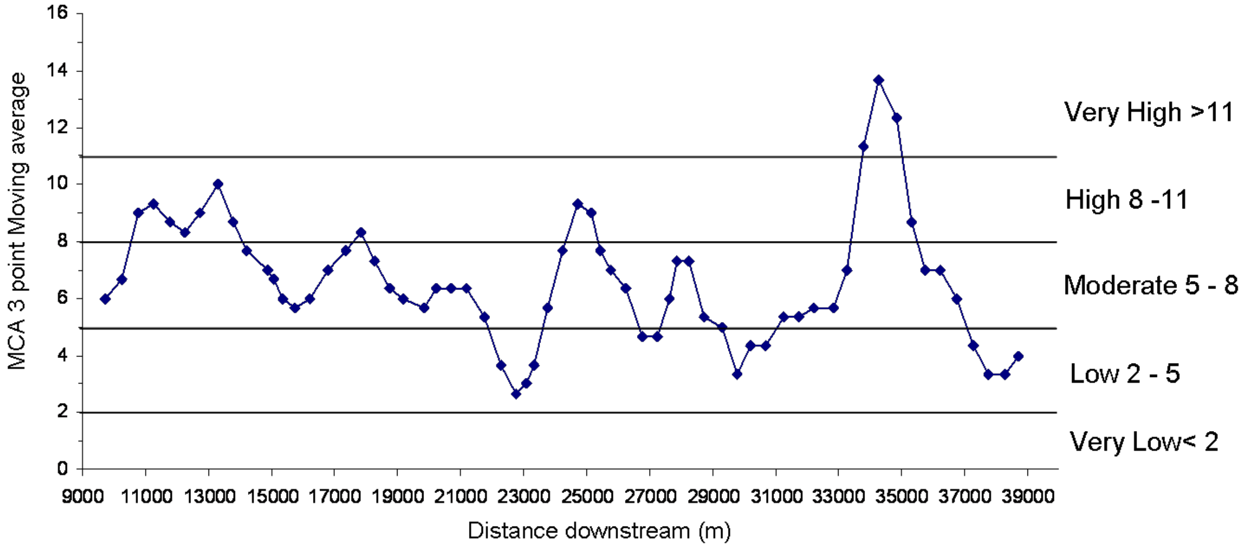


Figure 17 Smoothed MCA thresholds used to determine magnitude of geomorphic change based on calibration from the River Derwent, Cumbria during extreme flooding in 2009 and 2015

Figure 17 shows the thresholds for MCA scores selected on the basis of the best fit to the observed geomorphic change. Defining thresholds in this way is transparent, but ultimately subjective. It should also be recognised that even in the very low category, the scores are predicting some, albeit relatively small areas, of geomorphic change. For these reasons, it is recommended that the MCA values are used to identify hotspots and coldspots of flood effectiveness rather than attempting to quantify absolute values.

4.2 MCA and geomorphic change: River Kent

Ideally, for a full test a similar data set to that used to derive the MCA would be used. Unfortunately, no similar data sets were available at the time of the study. Instead, a fluvial audit carried out by JBA for the River Kent following Storm Desmond in 2015 was used. This data included lengths of bank erosion and points for the location of deposits. Unlike the Derwent geomorphic change data set that provided areas of erosion and deposition, there is no way of knowing how large or small each deposit was. Similarly, there is no indication of the extent of bank erosion.

An index of geomorphic change was derived using the Kent fluvial audit data. For the deposits the number of deposit points per segment were added together, while for bank erosion the length of polylines marked as eroding bank were combined. These values were then added together and standardised using z-scores:

$$Z = (i - x)/\sigma \qquad (7)$$

Where i is the value in a segment, x is the mean for all segments and σ is the standard deviation of values for all segments. A 3-point moving average was then applied to the values to create an index of total geomorphic change that was compared with the MCA scores.

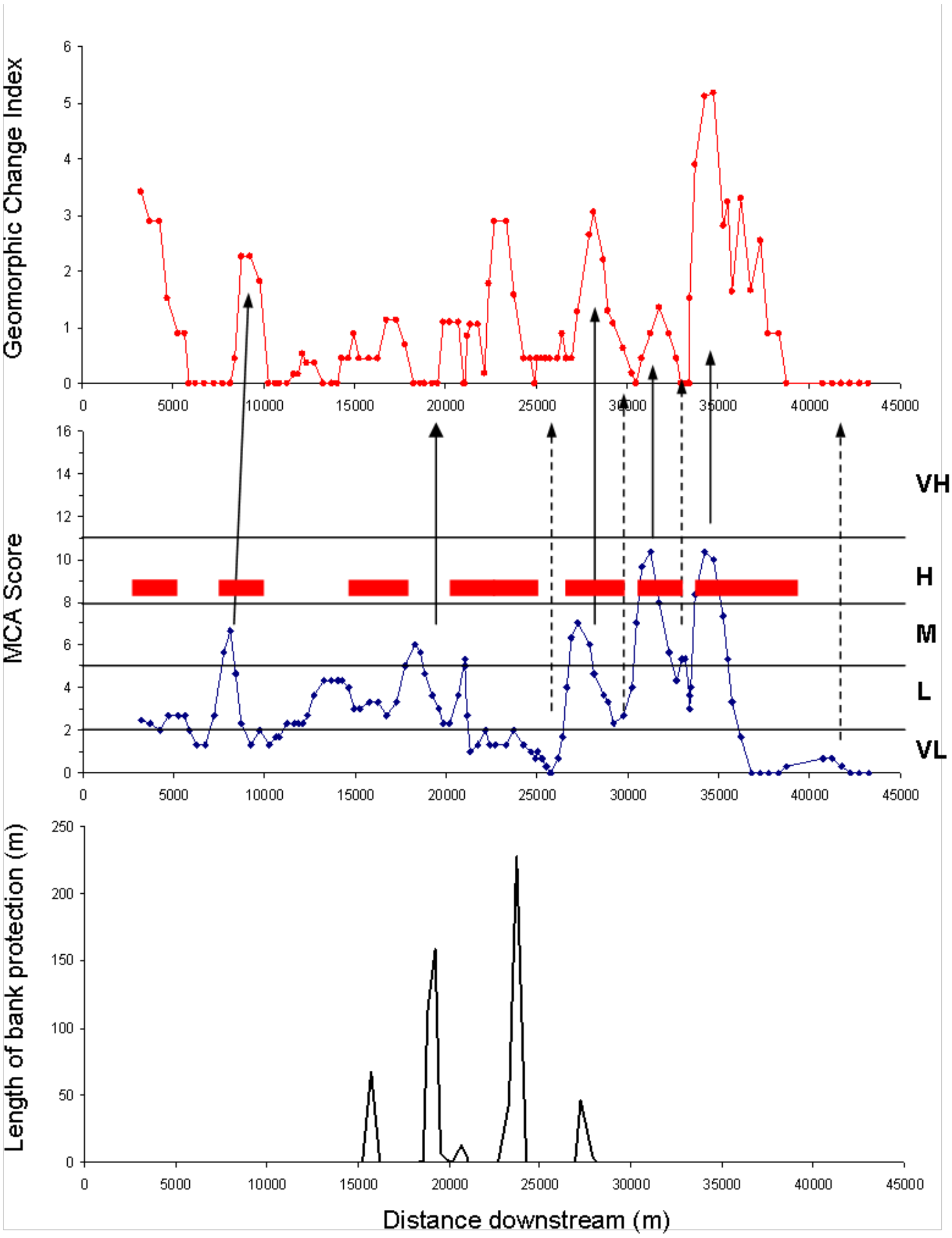


Figure 18 Geomorphic change index compared to MCA scores and proportion of bank protection for the River Kent based on fluvial audit data (JBA 2018)

Only broad comparison is relevant since the true scale of geomorphic change is not reflected in the index. The MCA scores predict broad scale variations in observed change and pick out most of the 'hotspots' and 'coldspots' of geomorphic change. Apparent differences are seen at the upstream end, and between 30,000 and 40,000 m when MCA predicts no change in an area of reducing but frequent bank erosion and deposition.

Figure 18 shows that the MCA scores broadly identify the zones of observed geomorphic change, but without direct comparable data this remains uncertain. Encouragingly, most of the hotspots of observed change are identified, although these are notably under predicted in the lower and upper parts of the river. It may be that the scale of change is smaller than the geomorphic index suggests (for example, high frequency of small deposits, and outer bank erosion would add up to large values in the index but would be lower in the MCA), but without additional data it remains impossible to confirm. An area of relatively high geomorphic change index at 23,000 to 24,000 m downstream is not predicted by the MCA.

Encouragingly, the MCA predicts relatively low geomorphic change in the lower gradient, unconfined reaches downstream of 38,000 m. Lack of confining margins switches sediment sources to bank erosion, while low stream power gradient reduces the overall magnitude of change that can be expected.

To fully independently test the MCA model, the project team recommend testing it against published studies where comparable geomorphic change data to the Derwent are available (for example, Surian and others, 2016, Thompson and Croke, 2013). These should extend to a range of other reaches, including confined valleys and unconfined rivers, characteristics of lowland case studies (for example, Magilligan, 1998). An example is the River Dee in Scotland, where comparable data to the Derwent geomorphic change data sets are available from SEPA following extreme flooding in the 2015 to 2016 Storm Frank (Wheaton pers. comm.).

4.3 Impact of human modification on flood plain confinement

The extent of modification to UK river flood plains is considered to be a factor in the geomorphic change experienced during extreme floods in the last decade, and particularly during events in Cumbria. To test this, the confining margins and constrictions on the River Derwent were modified by removing any that were man-made. The flood inundation polygon was altered by assuming the valley would flood to its margins in the absence of the confining margins – a reasonable assumption given modelled and observed valley inundation (Wong and others, 2014). The confining margins and stream power were then recalculated based on the new flood polygon.

The result was a change in the MCA scores (Figure 19 and Figure 20) for the River Derwent, which can be summarised as a loss of very high change classes, reduction in high change classes, and an increase in low change classes.

This provides, for the first time, a quantitative estimate of the effect of recent human modifications to the flood plain on the magnitude and location of geomorphic change. Crucially, the focus of human modifications is on the reaches downstream of Cockermouth, and particularly around the Camerton reach where the major changes in geomorphic change occurred during the flooding in 2009 and 2015.

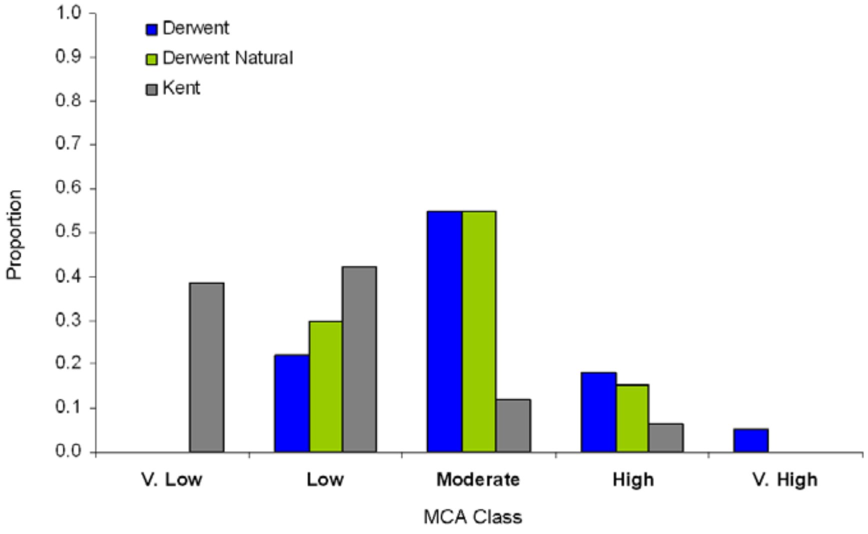


Figure 19 Proportion of total river length in different classes of geomorphic change

> *Overall, increased confinement and stream power gradient in the River Derwent creates higher magnitudes of geomorphic change compared to the River Kent. The effect of human modification to the flood plain of the Derwent over the past 150 years has increased the scale of geomorphic change relative to natural conditions.*

Confinement by railway embankments and mining spoil dumps led to erosion of the churchyard and the bridge collapse at Camerton. It also caused the avulsion of the channel and high levels of deposition on the adjacent flood plain. A similar effect occurred upstream at Papcastle, where confinement by road and railway embankments together with constriction at a road bridge generated conditions that forced erosion of the confining margins. Expansion of the flood plain immediately downstream of the constriction and confining margin provided a rapid reduction in stream power and a strongly negative stream power gradient. As flows expanded onto the flood plain, Miller (1995) predicted that water surface slope would steepen through the upstream constriction, generating high stream powers. At Papcastle, the combination of reducing stream power with an upstream erodible confining margin and high stream power constricted reach created both the sediment supply and reduction in transport that led to massive deposition on the flood plain. Removing the embankments and bridge constriction reduces the MCA score at both reaches from very high to moderate and from high to low respectively.

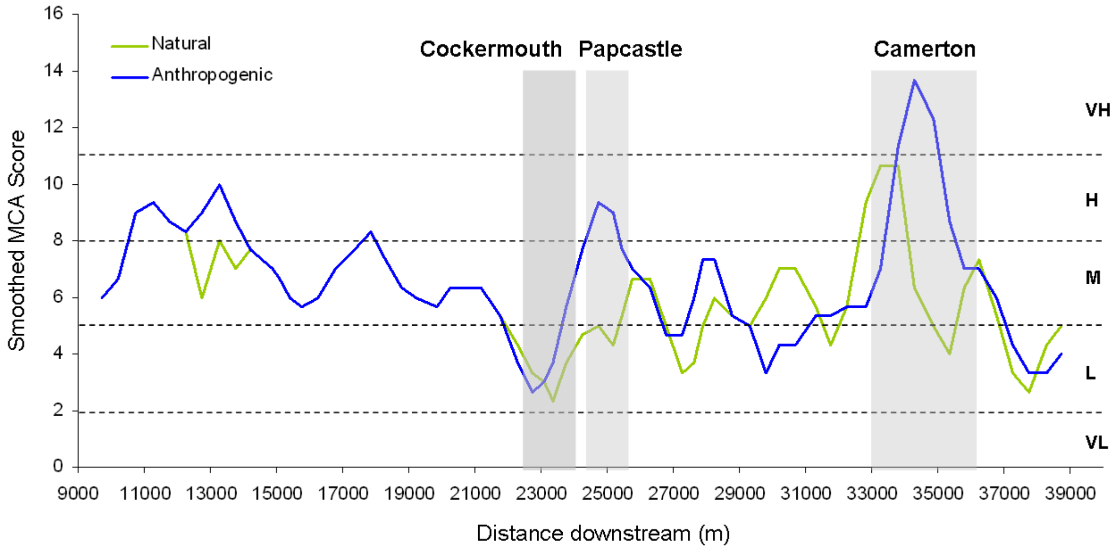


Figure 20 Change in predicted MCA values by removing human modifications to the flood plain

> *Note how major sites of geomorphic adjustment at Papcastle (high magnitude change) and Camerton (very high magnitude change) are reduced to low to moderate magnitude change when rail and road embankments and mining spoil heaps are removed, which currently confine the flow, increase stream power and extend areas of confining margins and sediment supply.*

4.4 Risk of geomorphic change

To predict the risk posed by geomorphic change the project team used the matrix shown in Figure 13 with the input values from the MCA and land use intensity layer.

Figures 21 and 22 show the resulting spatial pattern of risk relative to observed land use intensity class and observed geomorphic change for the River Derwent from Cockermouth to Camerton. Risk classes are generally moderate to low, with patches of high risk from geomorphic change, reflecting either high intensity land use or high rates of geomorphic change.

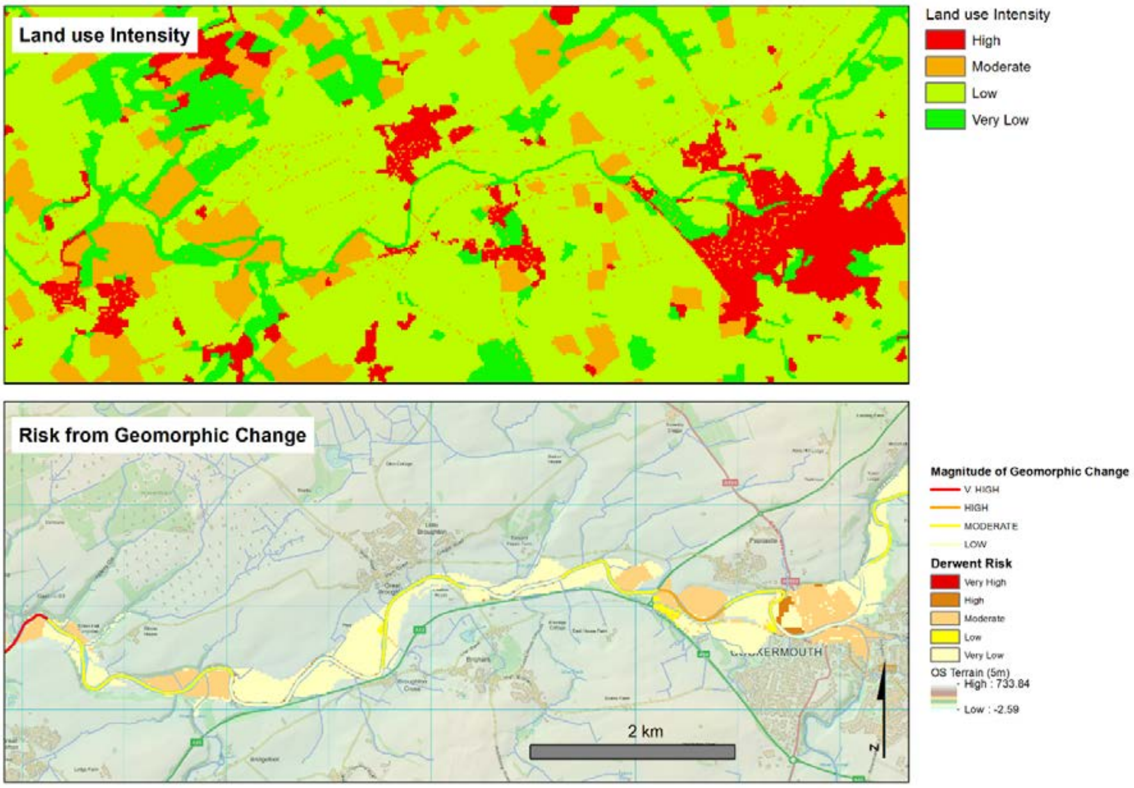


Figure 21 Comparison between the land use intensity classification of the River Derwent, Cockermouth to Camerton, and the resulting risk from geomorphic change

Despite high land use intensity in Cockermouth, the risk from geomorphic change is moderate to high because magnitude of change is predicted to be low. Conversely, at Camerton, despite low to very low land use intensity, risk is moderate to high because the magnitude of geomorphic change is very high.

The translation into risk classes emphasises the importance of recognising that geomorphic change is a natural process of channel adjustment to extreme flooding. Being able to differentiate between risks of geomorphic adjustment on low value land versus high value land allows resource managers to target potential remedial strategies, particularly if local information indicates that human modifications have caused the increased risk. In the Derwent case study, the majority of geomorphic change occurred on low intensity farmland (Figure 21), with hotspots resulting from human modifications such as railway embankments and mining at Camerton or road embankments and bridge constriction at Papcastle.

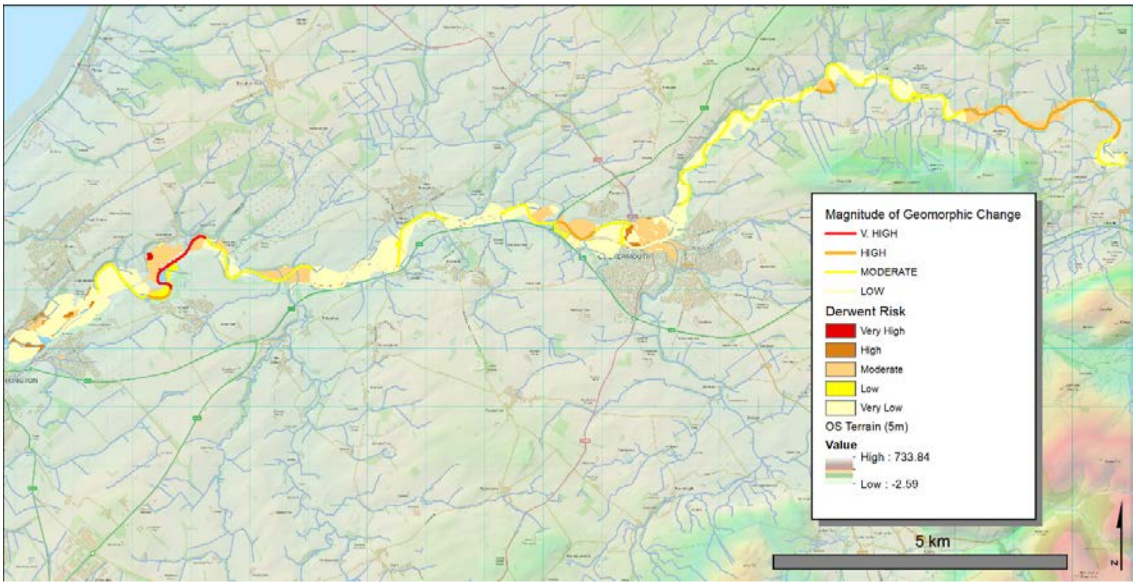


Figure 22 Risk of geomorphic change for the River Derwent, Cumbria

> *Risk hotspots are located in areas where the land use intensity is high (mainly road or urban areas) or where magnitude of geomorphic change is very high. The majority of the flood plain is in the moderate to low class of risk based on an agricultural land use dominated by grass pasture. The high risk areas in the reaches close to Lake Bassenthwaite reflect the confined nature of the valley at this point and the failure to account for the moderating effect of the lake on stream power. In reality, these reaches are low risk.*

The results for the River Kent (Figure 23) highlight how different apparently similar types of rivers can be. Both the Derwent and the Kent are partially confined rivers, but local differences in the erodibility of confining margins and stream gradients (lower in the Kent) together with differences in the land use intensity generate different risk profiles (Table 11). Overall, the Kent has more segments in lower categories of risk from geomorphic change than the Derwent. Anecdotal evidence supports this, although lack of comparable data on geomorphic change prevents a direct comparison.

Extending the analysis to a broader range of river case studies would be helpful in determining the range of risk classes and in improving the calibration of the geomorphic change classes used in the MCA analysis.

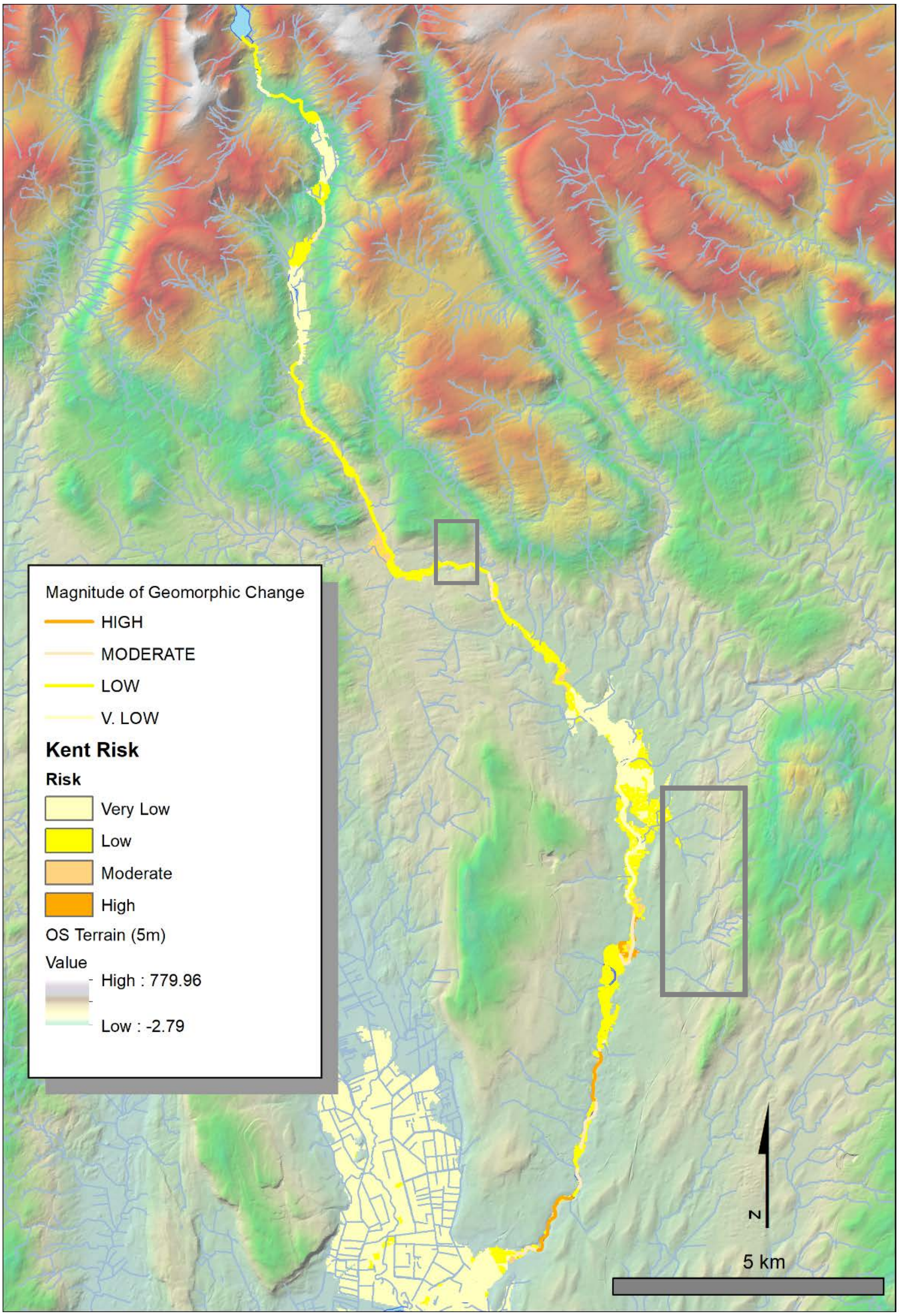


Figure 23 **Risk from geomorphic change predicted for the River Kent, Cumbria**

Low land use intensity together with generally very low to low magnitude of geomorphic change means the risk is low to very low. Hotspots of high risk are identified for the lower reaches where the channel is confined between erodible glacial sediments. The flood protection scheme through Kendal (grey box) limits the magnitude of predicted geomorphic change by constraining the width of the flood envelope, while reduced gradient reduces stream power. Lack of confinement through the town similarly reduces risk. Moderate risk is shown for the small urban area (small grey box) due to increased land use intensity.

4.5 The impact of flood plain modifications on risk from geomorphic change

Figure 24 and Table 7 show how the change in predicted geomorphic effectiveness by removing human modifications to the flood plain (not including urban areas) influences risk. The overall effect is to reduce risk and remove very high risk areas. This is shown most clearly at the Camerton Reach where confinement by mine spoil and resulting realignment of the river channel, together with confinement by the railway embankments caused extensive constrictions that forced bed and bank scour, avulsion and rapid deposition of eroded materials. Removing these confining margins reduces overall risk because predicted geomorphic effectiveness is reduced. Given that the railway is disused, the tool provides evidence that would include options to remove the embankments and remodel the mine spoil to protect the historical church and churchyard at Camerton.

Table 7 Percentage of flood plain in different classes of risk from geomorphic change

Risk	Derwent (Modified)	Derwent (Natural)	Kent
Very low	5.5	7.9	38.4
Low	69.0	70.9	54.0
Moderate	21.8	20.1	6.0
High	3.0	1.1	1.6
Very high	0.7	0.0	0.0

Renaturalising the Derwent flood plain removes the very high risk class and reduces high and moderate risk classes, resulting in an overall reduction in risk of geomorphic change. The Kent flood plain has a lower risk profile compared to the Derwent, resulting from an overall lower magnitude of predicted geomorphic change coinciding with lower intensity land uses.

The risk tool could be used to account for changes in land use intensity (future planning development), and/or modification to the flood plain. Since the focus is on extreme flooding, climate change scenarios are not necessarily relevant, although the tool can be used with any model outputs that predict stream power and flood inundation extent.

Since the tool is based on nationally available data sets, it would be conceptually possible to generate risk maps for 0.1 and 0.2% AEP floods across all rivers accepting the assumptions made in the flood modelling and in the development of the tool.

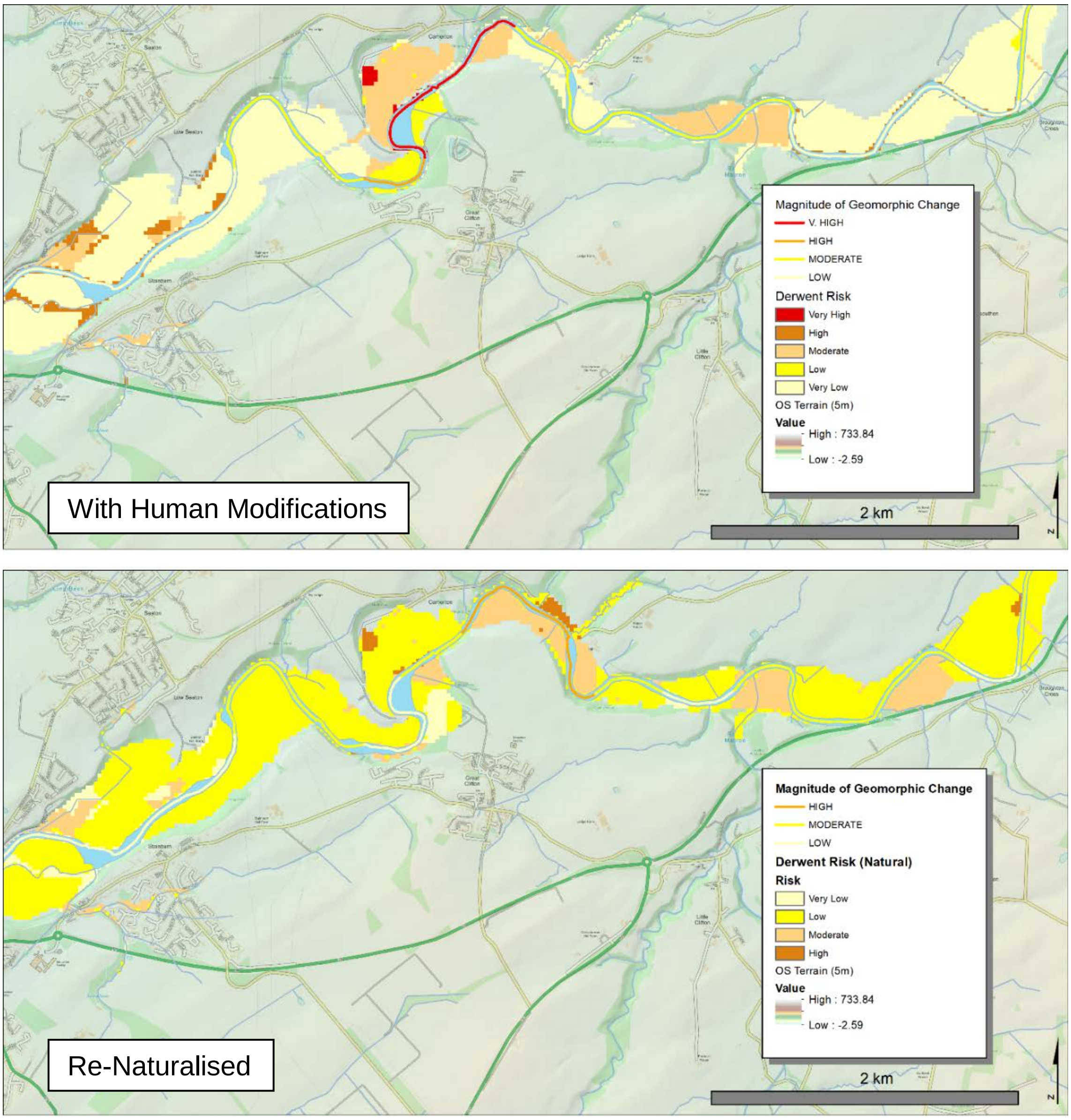


Figure 24 Difference in the risk from geomorphic change during extreme floods for the Camerton Reach of the Cumbrian River Derwent for current (upper panel) and for a scenario where human modifications have been removed

Overall, there is a reduction in risk throughout the reach, supporting the view that past modifications improve the likelihood of geomorphic change.

4.6 Towards a national risk-based assessment

The analysis and tools developed in this project resulted in a simple combination of 2 physically relevant measures – stream power gradient (change in stream power between 2 reaches) and area of erodible sediment to a reach. Producing both measures is conceptually simple but technically challenging in its current form. Improvements would include:

i. using locally-derived specific stream power gradient from existing 2D hydraulic modelling outputs for 0.2% or 0.1% AEP flood events

ii. land use intensity represents a simplified model of land use type with a class assigned to each type. It would be possible to use more sophisticated spatial data or existing estimates of land use value to refine the risk estimation

iii. using flood zone 2 polygons presents problems in applying the river confinement tool. The main problem is deriving a valley centreline in order to segment each valley into 500 m segments. Using the channel centreline instead (as used by other tools) does not allow you to estimate confinement. An important piece of work is to a) derive a confinement tool that works with UK data sets and b) if this is to be based on existing flood zone 2 polygons, these will need to be cleaned and simplified dissolving internal boundaries and removing all minor holes in the polygon

iv. The RiverScapes Confinement Tool http://confinement.riverscapes.xyz/ is used to create measures of confining margins (see Appendix A). Currently, this tool is unable to process an entire catchment due to topological issues with OS MasterMap WaterLayer and flood zone 2 data that are generating illogical situations that cause the current model to fail. The confinement tool is designed for US data and is generalised. So, there is a need to create a UK-specific confinement tool that can accommodate the complexity of the UK river network data.

v. The segmentation of the flood plain relies on a valley centreline to orientate the cross sections. Currently, creating a channel centreline using existing tools does not work without manual interventions. This prevents it being applied at a national or even catchment scale.

To be used nationally a tool needs to be able to extract confining margins from existing national data sets and generate flood stream power based on flow accumulation for 0.2% AEP flood events. The intermediate data set of channel centreline should be used as the basis for segmentation and reporting. This will remove many of the technical issues associated with deriving flood plain segments.

Developing the tools, the work needed to deploy them on a national scale, and the methodology needed to do this are discussed in Appendix A. The timescale required for development and implementation are discussed in section A8. Broadly, it is anticipated that:

- developing, testing and documenting the tools will take 2 to 3 months
- implementing the methodology across England and Wales will take around 14 to 18 months

4.7 Ability to simulate climate change

Given that we are dealing with the effects of extreme flood events, we are more interested in the impacts of climate change on the increased frequency rather than the scale of extreme flooding. The location and magnitude of geomorphic change is based on an extreme event scenario (>0.2% AEP). Given the model takes the outputs from flood model polygon and (recommended) estimates of stream power, then theoretically the model can be used where climate change scenarios of flood inundation are available.

4.8 Ability to simulate different discharges

The method can be applied to any flow provided that a flood outline and measure of stream power is available. Therefore, it would be possible to produce risk of geomorphic change maps for floods of different probability, like flood mapping. If flood inundation polygons were used, then values of channel confinement and area of sediment supply would change along with values of stream power gradient. This would tend to over predict geomorphic change given that lower flood magnitudes would not necessarily activate those areas of sediment supply. Therefore, a different assessment would need to consider whether lower discharge flood events were capable of mobilising boundary materials. Given that most risk and costs occur during extreme events, the project team recommend simply using either the 0.2% AEP (1:500) or 0.1% AEP (1:1,000) flooding outlines for national scale screening of risk of geomorphic change.

4.9 Ability to simulate channel management/ planning

Where channel management is mapped and characterised (degree of protection offered to river banks) and its effects simulated in flood models, this data will be included in the MCA method. Importantly, actions that increase or reduce confinement or constriction will result in variations to predicted geomorphic change. In this respect, the model is sensitive and can help to risk screen actions that modify flood plain land use, infrastructure and channel management. The model can also incorporate changes in channel planform where these modify the proportion of confinement. In a scenario mode, the model can be used to develop risk-based evidence for flood plain planning, for example, the siting of a new road or development or a change in farming where this increases intensity or value of the land.

Incorporating a simple land use intensity risk matrix provides a tool for interacting with interested groups. The values we have allocated to different land use intensity classes can be negotiated with local interested groups. For example, our current low score for pasture may in fact be vital to individual farmers at different times of the year. It would be possible to work with interested groups to derive a more accurate value for different classes. This would, in turn, change the pattern of risk up or down, but also support decision making.

5 Conclusions

5.1 Project influences

- Geomorphic change following recent extreme flooding has led to multi-million-pound damages, resulting in repairs and replacements to infrastructure, property, maintenance of flood risk assets, and debris clearance from property and farmland.
- Geomorphic changes have led to operational and strategic changes in flood risk management and increased awareness of geomorphic processes, notably in upland watercourse in the north-west and north-east areas of England.
- Geomorphic changes have changed interested groups' views of river management, with many calling for more dredging to be carried out and many welcoming catchment-based and natural flood management (CaBA/NFM) approaches.

5.2 Evidence review

- Geomorphologically effective floods are well-defined across a range of catchment sizes 0.9 to 4,000 km^2 by specific discharge values > 1.0 $m^3s^{-1}km^{-2}$. Increasing values above 1.0 $m^3s^{-1}km^{-2}$ results in more extensive geomorphic change. This value can be used to define a threshold discharge for risk of geomorphic change.
- Confinement and constriction are important concepts in flood effectiveness and can be modified by river and flood plain management. We recommend that maps of confinement and constriction are developed nationally and used to screen the impacts of a) natural channel planform change and b) proposed river or flood plain development.

5.3 Results

- Two important influences of geomorphic change were identified: the area of sediment supply from confining margins and the stream power gradient. Together they account for up to 74% of the variability in observed total geomorphic changes during storms in 2009 and 2015 on the River Derwent, Cumbria.
- A multi-criteria assessment (MCA) model successfully predicted 52% of the observed total geomorphic changes along the Cumbrian Derwent downstream of Lake Bassenthwaite. In an independent test, the model also predicted the main hotspots of geomorphic change observed along the River Kent following Storm Desmond. This accounts for 74% of observed variation but over predicts in upper reaches where the effect of the lake has not been factored into the stream power measure.
- A new risk model is developed using a novel land use intensity classification derived from the Land Cover Map 2015 and OS MasterMap road and rail network. A risk matrix integrates the magnitude of geomorphic change with land use intensity to predict areas at risk from geomorphic

change. The MCA model predicts the change in magnitude and risk of geomorphic change resulting from these modifications.

5.4 Implications

The modelling undertaken in this project showed the following potential implications.

- Human modification to the River Derwent flood plain through mining, road and railway embankments has resulted in increased confinement and constriction that forced higher magnitude geomorphic changes than would have occurred under natural conditions.
- Redesigning/removing human modifications to the Derwent flood plain results in reduced risk from geomorphic change during extreme floods.
- Comparison between the 2 case study rivers reveals different levels of risk from geomorphic change – lower risk overall on the River Kent compared to the River Derwent.
- The ability to predict risk resulting from geomorphic change for the first time provides an opportunity to influence planning decisions across a range of flood plain development. It also provides a framework for discussion with interested groups by being able to quickly model the impacts of changes in land use intensity and restoration.

5.5 Recommendations

i. The risk-based MCA model could be tested on comparative data sets to the Derwent calibration site. It is recommended that the model could be tested on the River Dee, Scotland where similar data sets on geomorphic change are available. It is also recommended that suitable data sets could be generated by interpreting air photos post Storm Desmond and Storm Frank. Candidates include the South Tyne, Eden and Caldew.

ii. Existing modelling of discharge and water surface elevation for 0.2% or 0.1% AEP flood events can be used to calculate stream power gradients nationally.

iii. A tool that can implement the MCA analysis across all types of river nationally could be developed. This will require a new method for generating confining margins suitable for UK data sets.

iv. While the literature review provides scientific evidence to help understand the effects of extreme flooding on geomorphic change in river networks, it does not specifically identify the scale, costs, operational and strategic impact of geomorphic changes. In any future phases of this project a survey (based on the pilot carried out at this stage) could be sent out to operational geomorphologists within the Environment Agency. The aim of this would be to place the literature review and case study evidence in the wider national context, and to make sure that project outcomes are addressing real life experience of flood impacts from within the Environment Agency.

References

Acreman MC. 1989 ‘Extreme historical floods and maximum flood estimation’ J.CIWEM, 3, 404 to 412

Bagnold RA. 1966 ‘An Approach to the Sediment Transport Problem from General Physics’ U.S. Geological Survey Professional Paper 422-I; U.S. Government Printing Office: Washington, DC, USA, 1966; p. 42

Baker VR. 1977 ‘Stream channel response to floods with examples from central Texas’ Geological Society of America Bulletin 88, 1057 to 1071

Barker L, Hannaford J and Parry S. 2016 ‘Severity of the December 2015 floods-preliminary analysis’ Briefing note

Bizzi S and Lerner D. 2013 ‘The use of stream power as an indicator of channel sensitivity to erosion and deposition processes’ River Res. Appl. http://dx.doi.org/10.1002/rra.2717

Brown AG, Copper L, Salisbury CR and Smith DN. 2001 ‘Late Holocene channel changes of the Middle Trent: channel response to a thousand-year flood record’ Geomorphology 39, 69 to 82

Buraas EM, Renshaw CE, Magilligan FJ and Dade WB. 2014 ‘Impact of reach geometry on stream channel sensitivity to extreme floods’ Earth Surf. Process. Landf. 39, 1778 to 1789

Carling PA. 1986 ‘The Noon Hill Flash Floods; July 17th, 1983. Hydrological and Geomorphological Aspects of a Major Formative Event in an Upland Landscape’ Transactions of the Institute of British Geographers, 11: 105 to 118

Carling P and Beven K. 1989 ‘The hydrology, sedimentology and geomorphological implications of floods: an overview’ In: Beven K, Carling P. (Eds.) ‘Floods: Hydrological, Sedimentological and Geomorphological Implications’ Wiley, Chichester, pp. 1 to 9

Castro JM and Thorne CR. 2019 ‘The Stream Evolution triangle: Integrating Geology, Hydrology and Biology’ River Research and Applications, 35:315 to 326

Chiverrell RC, Sear DA, Warburton J, Macdonald N, Schillereff DN, Dearing JA, Croudace IW, Brown J and Bradley J. 2019 ‘Using lake sediment archives to improve understanding of flood magnitude and frequency: recent extreme flooding in northwest UK’ Earth Surface Processes and Landforms, DOI: 10.1002/esp.4650

Church M. 2006 ‘Bed material transport and the morphology of alluvial river channels’ The Annual 828 Review of Earth and Planetary Science 34: 325 to 354

Clark MJ and Richards KJ. 2002 ‘Supporting complex decisions for sustainable river management’ Aquatic Conservation: Marine and Freshwater Ecosystems, 12: 471 to 483

Comiti F, Righini M, Nardi L, Lucía A, Amponsah W, Cavalli M, Surian N, Marchi L, Rinaldi M, Borga M. 2015 ‘Channel widening during extreme floods: how to integrate it within river corridor planning?’ Proceedings of Interpraevent 2016. 477 to 486

Costa JE and O'Connor JE. 1995 ‘Geomorphically effective floods’ In: Costa JE, Miller AJ, Potter KW, Wilcock P. (Eds.) ‘Natural and Anthropogenic Influences in Fluvial Geomorphology Monograph 89’ American Geophysical Union, Washington, DC, pp. 45 to 56

Dean DJ, Schmidt JC. 2013 ‘The geomorphic effectiveness of a large flood on the Rio Grande in the Big Bend region: insights on geomorphic controls and post-flood geomorphic response’ Geomorphology 201, 183 to 198

Death RG, Fuller I C and Macklin MG. 2015 ‘Resetting the river template: the potential for climate-related extreme floods to transform river geomorphology and ecology’ Freshw Biol, 60: 2,477 to 2,496

Environment Agency. 2018 ‘Estimating the economic costs of the 2015 to 2016 winter floods’ Environment Agency, Horizon House, Deanery Road, Bristol BS1 5AH, 50pp

Fryirs KA and Brierley GJ. 2018 ‘What's in a name? A naming convention for geomorphic river types using the River Styles Framework’ PLoS ONE, 13(9): e0201909. https://doi.org/10.1371/journal.pone.0201909

Fryirs KA and Brierley GJ. 2010 ‘Antecedent controls on river character and behaviour in partly confined valley settings: Upper Hunter catchment, NSW, Australia’ Geomorphology 117: 106 to 120

Fryirs KA, Wheaton JM and Brierley GJ. 2016 ‘An approach for measuring confinement and assessing the influence of valley setting on river forms and processes’ Earth Surf Proc Landforms; 41: 701 to 710

Fryirs KA. 2017 ‘River sensitivity: a lost foundation concept in fluvial geomorphology’ Earth Surface Processes and Landforms 42: 55 to 70. DOI: 10.1002/esp.3940

Fryirs KA, Wheaton JM and Brierley GJ. 2016 ‘An approach for measuring confinement and assessing the influence of valley setting on river forms and processes’ Earth Surface Processes and Landforms 41: 701 to 710. DOI: 10.1002/esp.3893

Fuller IC. 2008 ‘Geomorphic impacts of a 100-year flood: Kiwitea Stream, Manawatu catchment, New Zealand’ Geomorphology 98: 84 to 95

Gartner JD, Dade WB, Renshaw CE, Magilligan FJ and Buraas EM. 2015 ‘Gradients in stream power influence lateral and downstream sediment flux in floods’ Geology http://dx.doi.org/10.1130/G36969.1

Hall J and others. 2014 ‘Understanding flood regime changes in Europe: A state-of-the-art assessment’ Hydrology and Earth System Sciences 18, 2,735 to 2,772

Hallegatte S, Green C, Nicholls RJ and Corfee-Morlot J. 2013 ‘Future flood losses in major coastal cities’ Nature Climate Change 3, 802 to 806

Harvey AM. 1991 ‘The influences of sediment supply on the channel morphology of upland streams: Howgill Fells, North West England’ Earth Surface Processes and Landforms, 16, 675 to 684

Harvey AM. 2007 ‘Differential recovery from the effects of a 100-year storm: significance of long-term hillslope–channel coupling; Howgill Fells, North West England’ Geomorphology 84, 192 to 208

Hassan M, Church M and Ashworth PJ. 1992 ‘Virtual Rate and Mean Distance of Travel of Individual Clasts in Gravel-Bed Channels. Earth Surface Processes and Landforms’ 17. 617 to 627. 10.1002/esp.3290170607

Hooke JM. 2015 ‘Variations in flood magnitude – effect relations and the implications for flood risk assessment and river management’ Geomorphology, 251, 91 to 107

Huntingford C, Marsh T, Scaife AA, Kendon EJ, Hannaford J, King AL and Allen MR. 2014 ‘Potential influences on the United Kingdom's floods of winter 2013/14’ Nature Climate Change, 4, 769 to 777

JBA. 2018 on behalf of the Environment Agency, River Kent Fluvial Audit

Joyce HM, Hardy RJ, Warburton J and Large ARG. 2018 ‘Sediment continuity through the upland sediment cascade: geomorphic response of an upland river to an extreme flood event’ Geomorphology 317: 45 to 61

Kendon M, McCarthy M, Jevrejeva S, Matthews A and Legg T. 2019 ‘State of the UK Climate’ 2018 International Journal of Climatology, Volume 39, Pages: 1 to 55

Knight DW and Shiono K. 1996 ‘River channel and floodplain hydraulics’ In ‘Floodplain processes’ Edited by: Anderson MG, Walling DES and Bates PD 139 to 181. Chichester: John Wiley

Knighton AD. 1998 ‘Fluvial Forms and Processes: A New Perspective’ Arnold, London (383pp)

Kochel RC. 1988 ‘Geomorphic impact of large floods: Review and new perspectives on magnitude and frequency’ In Baker VR, Kochel RC and Patton PC. (Eds) ‘Flood Geomorphology’ J. Wiley and Sons, New York, 169 to 187

Langhammer J. 2010 ‘Analysis of the relationship between the stream regulations and the geomorphologic effects of floods’ Nat. Hazards 54 (1), 121 to 139

Lea DM and Legleiter CJ. 2016 ‘Mapping spatial patterns of stream power and channel change along a gravel-bed river in northern Yellowstone’ Geomorphology 2016, 252, 66 to 79

Lewin J. 2013 ‘Enlightenment and the GM floodplain’ Earth Surf. Process. Landf. 38 (1),17 to 29

Magilligan FJ. 1992 ‘Thresholds and the spatial variability of flood power during extreme floods’ Geomorphology, 5, 373 to 390

Magilligan FJ, Phillips JD, James LA and Gomez B. 1998 ‘Geomorphic and sedimentological controls on the effectiveness of an extreme flood’ J. Geol. 106, 87 to 95

Merwade V, Cook A and Coonrod J. 2008 ‘GIS techniques for creating river terrain models for hydrodynamic modelling and flood inundation mapping’ Environ. Model. Softw., 23, 1,300 to 1,311

Middelkoop H and Asselman NE. 1998) ‘Spatial variability of floodplain sedimentation at the event scale in the Rhine–Meuse delta, The Netherlands’ Earth Surf. Process. Landforms, 23: 561-573. doi:10.1002/(SICI)1096-9837(199806)23:6<561::AID-ESP870>3.0.CO;2-5

Milan DJ. 2012 ‘Geomorphic impact and system recovery following an extreme flood in an upland stream: Thinhope Burn, northern England, UK’ Geomorphology 138, 319 to 328

Miller AJ. 1990 ‘Flood hydrology and geomorphic effectiveness in the central Appalachians’ Earth Surf. Process. Landf. 15, 119 to 134. http://dx.doi.org/10.1002/esp. 3290150203

Miller AJ. 1995 ‘Valley morphology and boundary conditions influencing spatial patterns of flood flow’ In: Costa JE, Miller AJ, Potter KW, Wilcock PR. (Eds.) ‘Natural and Anthropogenic Influences in Fluvial Geomorphology’ Geophysical Monograph, vol. 89. American Geophysical Union, pp. 57 to 81

Miller JD, Kjeldsen TR, Hannaford J and Morris DG. 2013 ‘A hydrological assessment of the November 2009 floods in Cumbria, UK’ Hydrology Research 44, 180

Nanson GC and Croke JC. 1992 ‘A genetic classification of floodplains’ Geomorphology 4, 459 to 486

Newson MD. 1980 ‘The geomorphological effectiveness of floods: a contribution stimulated by two recent events in mid-Wales’ Earth Surface Processes, 5, 1 to 16

Newson MD. 1989 ‘Flood effectiveness in river basins: progress in a decade of drought’ In Beven K and Carling PA. (Eds) ‘Floods, hydrological, sedimentological and geomorphological implications’ J Wiley and Sons, Chichester, UK, 151 to 169

O'Brien GR, Wheaton JM, Fryirs K, Macfarlane WW, Brierley G, Whitehead K, Gilbert J and Volk C. 2019 ‘Mapping valley bottom confinement at the network scale’ Earth Surf. Process. Landforms, https://doi.org/10.1002/esp.4615

O'Gorman PA and Schneider T. 2009 ‘The physical basis for increases in precipitation extremes in simulations of 21st-century climate change’ Proceedings of the National Academy of Sciences of the United States of America 106, 14,773 to 14,777, doi:10.1073/pnas.0907610106

Parker C, Thorne CR and Clifford NJ. 2015 ‘Development of ST:REAM: A reach-based stream power balance approach for predicting alluvial river channel adjustment’ Earth Surf. Process. Landf., 40, 403 to 413

Parry S, Barker L, Prosdocimi I, Lewis M, Hannaford J and Clemas S. 2016 ‘Hydrological summary for the United Kingdom: December 2015’

Pattison I and Lane SN. 2012 ‘The relationship between Lamb weather types and long-term changes in flood frequency, River Eden, UK’ Int. J. Climatology, 32 (13), 1,971 to 1,989

Petit F, Gob F, Houbrechts G and Assani AA. 2005 ‘Critical specific stream power in gravel-bed rivers’ Geomorphology 69: 92 to 101

Richards K. 1999 ‘The magnitude–frequency concept in fluvial geomorphology: a component of a degenerating research programme?’ Z. Geomorphol. Suppl. 115, 1 to 18

Riley W and others. 2018 ‘Small Water Bodies in Great Britain and Ireland: Ecosystem function, human-generated degradation, and options for restorative action’ Science of the Total Environment, 645:1,598 to 1,616

Rinaldi M, Amponsah W, Benvenuti M, Borga M, Comiti F, Lucía A, Marchi L, Nardi L, Righini M and Surian N. 2016 ‘An integrated approach for investigating geomorphic response to an extreme flood event: methodological framework and application to the October 2011 flood in the Magra River catchment, Italy’ Earth Surface Processes and Landforms 41: 835 to 846

Sargood MB, Cohen TJ, Thompson CJ and Croke J. 2016 ‘Hitting rock bottom: morphological responses of bedrock-confined streams to a catastrophic flood’ Earth Surf. Dynam., 3, 265 to 279, 2015

Sear D, Wheaton J, Neal J, Andersen E, Leyland J, Hornby D, Bates P, Murdoch A and Dearing J. 2017 ‘Valley and Human Controls on the Geomorphic Responses to an Extreme Flood’ Cumbrian Floods Partnership Geomorphology Workshop. Penrith, UK

Sear DA, German S, Hill CT and Branson J. 2000 ‘Impact of recent floods on channel morphology and physical habitat using RHS re-survey’ Environment Agency Report W5A-064, WRc, 41pp

Sear D, Newson M, Hill C, Old J and Branson J. 2009 ‘A method for applying fluvial geomorphology in support of catchment-scale river restoration planning’ Aquat. Conserv. Mar. Freshw. Ecosyst.19: 506 to 519

Stocker TE. 2013 ‘Climate change: the physical science basis’: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change

Surian N, Righini M, Lucía A, Nardi L, Amponsah M, Benvenuti M, Borga M, Cavalli M, Comiti F, Marchi L, Rinaldi M, Viero A. 2016 ‘Channel response to extreme floods:insights on controlling factors from six mountain rivers in northern Apennines, Italy’ Geomorphology 272: 78 to 91

Thompson C, Croke J. 2013 ‘Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer valley, southeast Queensland, Australia’ Geomorphology 197, 156 to 169

Thorne CR, Biedenharn DS, Hey RD, Soar PJ and Watson CC. 1999 ‘Effective discharge calculation for channel restoration design: Calculation’, Proceedings of the International Water Resources Engineering Conference, Seattle, August 1999, Raymond Walton and Ronald E. Nece (eds.), EWRI-ASCE, (CD ROM), ISBN 1-887201-25.4, 10p

Van Appledorn M, Baker ME and Miller AJ. 2019 ‘River-valley morphology, basin size, and flow-event magnitude interact to produce wide variation in flooding dynamics’ Ecosphere 10 (1) doi:10.1002/ecs2.2546

Wheaton JM, Brasington J, Darby SE, Sear DA. 2010 ‘Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets’ Earth Surf. Process. Landf. 35, 136 to 156

Wichersk W, Dethier DP and Ouimet WB. 2017 ‘Erosion and channel changes due to extreme flooding in the Fourmile Creek catchment, Colorado’ Geomorphology 294 (2017) 87 to 98

Wong JS, Freer JE, Bates PD, Sear DA, Stephens EM. 2015 ‘Sensitivity of a hydraulic model to channel erosion uncertainty during extreme flooding’ Hydrol. Process. 29, 261 to 279

Yochum SE, Sholtes JS, Scott JA, Bledsoe BP. 2017 ‘Stream power framework for predicting geomorphic change: The 2013 Colorado Front Range flood’ Geomorphology 292: 178 to 192

Appendix A: Tool development

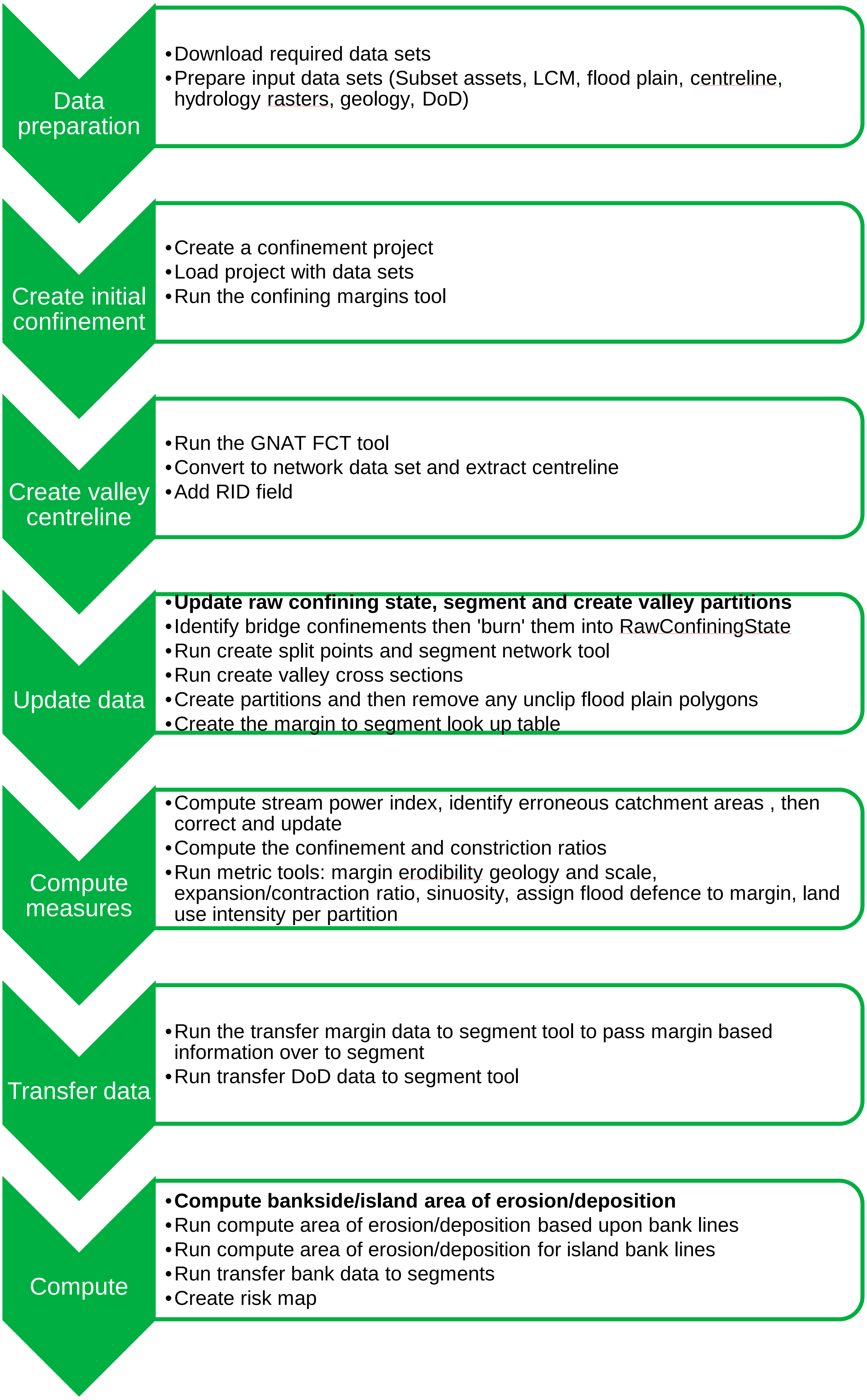
A1 Deriving measures of influencing factors

The process for working out the risk of geomorphic change was to segment the network, develop confinement-related measures and join these to the river segments. This would allow confinement to be mapped, MCA scores to be calculated and risk due to geomorphic change based on intensity of land use to be identified.

An ESRI ArcGIS 10.6 toolbox was developed creating a 22-step workflow for computing the risk of geomorphic change. The workflow steps can be broadly grouped into 4 stages: data preparation, spatial processing, creating measures and transferring measures to segmented river network.

Note: version ArcGIS 10.2.2 is not likely to be supported by ESRI and any tool development in earlier versions would likely need recoding from the 10.6 version on which this project's outputs have been based.

A comprehensive Help file was developed to describe and support the workflow. It describes input data sets and what is needed to prepare them, the outputs of tools and how they are subsequently used, a detailed breakdown of each tool and their expected parameters, outputs and usage and an overview workflow diagram (Figure A1).



Data preparation

- Download required data sets
- Prepare input data sets (Subset assets, LCM, flood plain, centreline, hydrology rasters, geology, DoD)

Create initial confinement

- Create a confinement project
- Load project with data sets
- Run the confining margins tool

Create valley centreline

- Run the GNAT FCT tool
- Convert to network data set and extract centreline
- Add RID field

Update data

- **Update raw confining state, segment and create valley partitions**
- Identify bridge confinements then 'burn' them into RawConfiningState
- Run create split points and segment network tool
- Run create valley cross sections
- Create partitions and then remove any unclip flood plain polygons
- Create the margin to segment look up table

Compute measures

- Compute stream power index, identify erroneous catchment areas , then correct and update
- Compute the confinement and constriction ratios
- Run metric tools: margin erodibility geology and scale, expansion/contraction ratio, sinuosity, assign flood defence to margin, land use intensity per partition

Transfer data

- Run the transfer margin data to segment tool to pass margin based information over to segment
- Run transfer DoD data to segment tool

Compute

- **Compute bankside/island area of erosion/deposition**
- Run compute area of erosion/deposition based upon bank lines
- Run compute area of erosion/deposition for island bank lines
- Run transfer bank data to segments
- Create risk map

Figure A1 The developed workflow for computing geomorphic change

Not all steps (for example, bank lines) are required to compute the final risk map, but they were part of the research and development of this project.

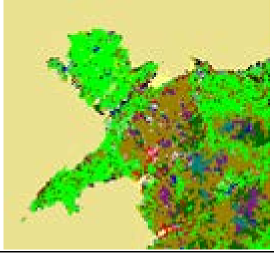
The developed tools are either model-only tools, python scripts or python toolboxes (developed by South Fork Research Inc.). All source code is open source and used through the ArcGIS geo-processing framework. It is worth noting that the Confinement Tool developed by South Fork Research Inc. (Source: https://github.com/Riverscapes/ConfinementTool) required intervention, editing the source code to allow it to work with UK data and fixing bugs. It was also enhanced to allow downstream processing logic to work.

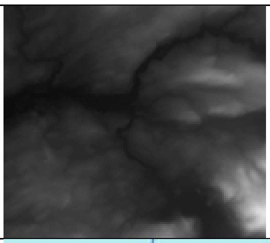
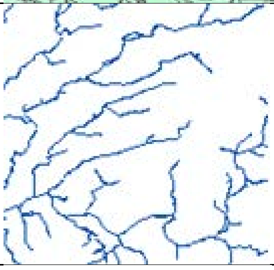
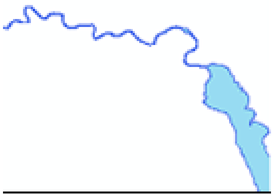
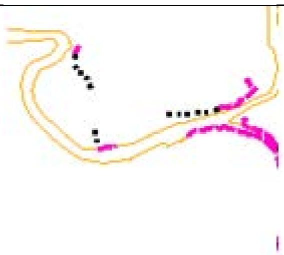
A2 Input data sets

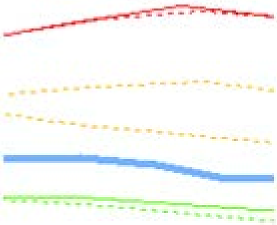
To complete the multi-stepped workflow a variety of input data sets were obtained and used to construct the flood plain and confinement margin measures. Table A1 lists the raw input data and indicates if significant data preparation is required.

Table A1 Input data sets

The Preparation column indicates if the data set required significant preparation beyond any usual download and import.

Dataset name	Source	Example	Preparation
BGS 1:50K Superficial	https://digimap.edina.ac.uk/		No
BGS 1:50K Bedrock	https://digimap.edina.ac.uk/		No
CEH 2015 Land Cover Map	https://digimap.edina.ac.uk/		Yes

Dataset name	Source	Example	Preparation
OS terrain (5 m)	https://digimap.edina.ac.uk/		No
Flow accumulation raster	Derived from OS Terrain		Yes
OS MasterMap Topographic Area	https://digimap.edina.ac.uk/		No
OS MasterMap WaterLayer	https://digimap.edina.ac.uk/		Yes
OS River Bank	MasterMap Topographic Area		Yes
Environment Agency flood zone 2 (valley bottom)	https://environment.data.gov.uk/		Yes
Environment Agency flood defence structures **(with attributes)**	https://environment.data.gov.uk/		Yes

Dataset name	Source	Example	Preparation
DEM of Difference	GCD data from NERC project		No
Bank lines 2009 and 2015	Past project and aerial photography obtained from https://environment.data.gov.uk/		Yes

A3 Data preparation

A detailed description of all data preparation is described in the Help file, which can be accessed from: https://github.com/Hornbydd/ConfinementTool/blob/master/UC1476_Help

Three main data preparation stages are briefly described below:

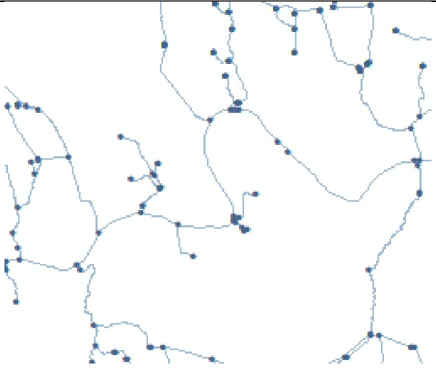
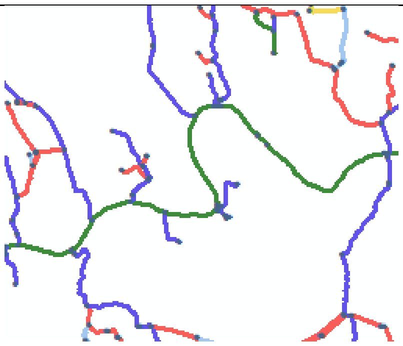
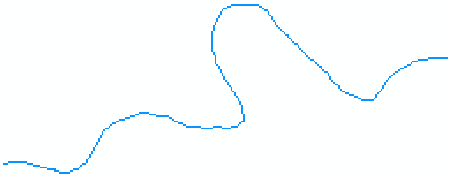
- **Land cover** – The CEH LCM 2015 25 m raster is reclassified into a land use intensity raster, recoding the LCM classes into very low/low/moderate/high classes. As part of the reclassification process, OS MasterMap roads and rail polygons are stamped into the raster before the reclassification. A tool was developed to simplify this data preparation step.
- **River network** – OS WaterLayer provided as 5 km 'fuzzy-edged' tiles in GML, duplicated geometry had to be removed. The network was simplified by dropping all polylines that were not Primacy 1. This dropped loops to create a single threaded network. The network was then encoded with Hack order and this provided the attribution required to simplify the network into 'branches' that can be used with linear referencing.
- **Valley bottom** – The Environment Agency flood zone 2 is used as the valley bottom layer for the confinement tool. Only polygons intersecting the main stem of the Derwent were kept. These were then manually cleaned up dissolving internal boundaries and dropping small holes. A tool was developed to remove larger holes only if the difference in mean elevation of the interior hole was less than the immediate surrounding elevation pixels by 3 m. This would leave holes in the valley bottom layer considered to be significant topographic highs in the flood plain.

A4 Understanding the levels of segmentation

Fundamental to developing the MCA scores and ultimately the risk class is how the river network is split up into differing levels of segmentation. Table A2 outlines each level; these are generated during the data preparation stage and spatial processing.

Table A2 The levels of network coding required to create a segmented main stem for analysis

† = *www.rivex.co.uk*

Data set	Example	Description
OS WaterLayer		The OS WaterLayer provides a topologically correct network where lines connect at nodes. This layer is processed to remove loops by dropping lines where Primacy is not equal to 1, therefore creating a single threaded network (see Appendix A, A7).
Hack order encoded network		Using RivEX†, Hack order is encoded into the base network. This is a hierarchical numbering system that can be applied to single thread networks. All lines to their source have the same order.
Main stem		Identifying the Hack order for the main Derwent channel allows the main stem to be extracted, dissolved into a single line and converted to a measured line with distance encoded into the M value.
Segments		Split points can be easily created along a measured line and these are used to segment the main stem into 500 m reaches, the chosen length for this analysis.

A5 Spatial processing

The Help file and numbered tool names guide the user through a sequence of spatial processing. The main steps are listed in Table A3.

Table A3 Overview of main steps for generating the intermediate spatial data sets and subsequent measures that are then joined back to the river segment

Main step	Task	Description
1	Creating the main stem of the Derwent	Extract a single route by using Hack order, dissolve, convert to PolylineM and calibrate distance along the polyline. This creates the main stem of the Derwent from the outflow of lake Bassenthwaite along which other data can measure.
2	Creating confining margins	This confinement tool, developed by South Fork Research Inc., creates the confinement margins and a segmentation of the main stem line encoding confinement/constriction.
3	Generating the valley centreline	Using Geomorphic Network and Analysis Toolbox (GNAT) toolbox a Thiessen skeleton is extracted from the valley bottom layer. This is then converted to a network data set, network stops manually placed along the network are then solved to create an extract that is exported, creating a valley centreline complimentary to the main stem.
4	Identify bridge confinements and stamp back into step2 output	Constrictions caused by bridges are not extracted by the confining margins tool (step 2). These are extracted from OS MasterMap following similar logic and then stamped back into the confining margins centreline.
5	Segment river network	This tool identifies bridge centre points, calculates regularly spaced 500 m points along each branch of the network (each encoded by unique Hack order) and uses these split points to segment the network. Therefore, a segment can only be a maximum length of 500 m, but it can be shorter if a bridge point falls between spaced points. It is these segments along the branch defining the main stem that are used in the MCA scoring.
6	Create valley cross sections	This tool takes the segmented network, branch ID for the main stem, valley centreline and valley bottom to generate sensible valley cross sections (ideally using Lidar or OS Terrain data). Including the valley centreline allows for the cross section to be orientated from the river centreline across the valley bottom. Some manual correction may be required. Cross sections are created at the split points used to segment the network.
7	Partition of valley bottom	With the valley cross sections calculated, the valley bottom can be partitioned into areas for each segment. A second tool is run to deal with incoming tributaries and their contributing flood plain. This is a semi-automated process that needs human intervention to quality control the results.
8	Margin to segment lookup table	This table provides the lookup to associate data collected along the margin back to the segment.

Main step	Task	Description
9	Generate measures	A sequence of tools is then run to calculate various measures that are joined to the segments along the main stem. These are: • stream power index • confinement and constriction ratio • margin erodibility • flood plain expansion/contraction ratio • sinuosity • margin flood defence • land use intensity per partition These measures are then transferred back to the segment.

Details of each main step outlined in Table A3 are held in the Help file. Some steps simply involve various tools being run, while others require human intervention to deal with extreme cases within the data sets (for example, highly tortuous channel). Figure A2 shows the various spatial data sets and their relationship to one another. Measures developed from these are encoded into main stem segments.

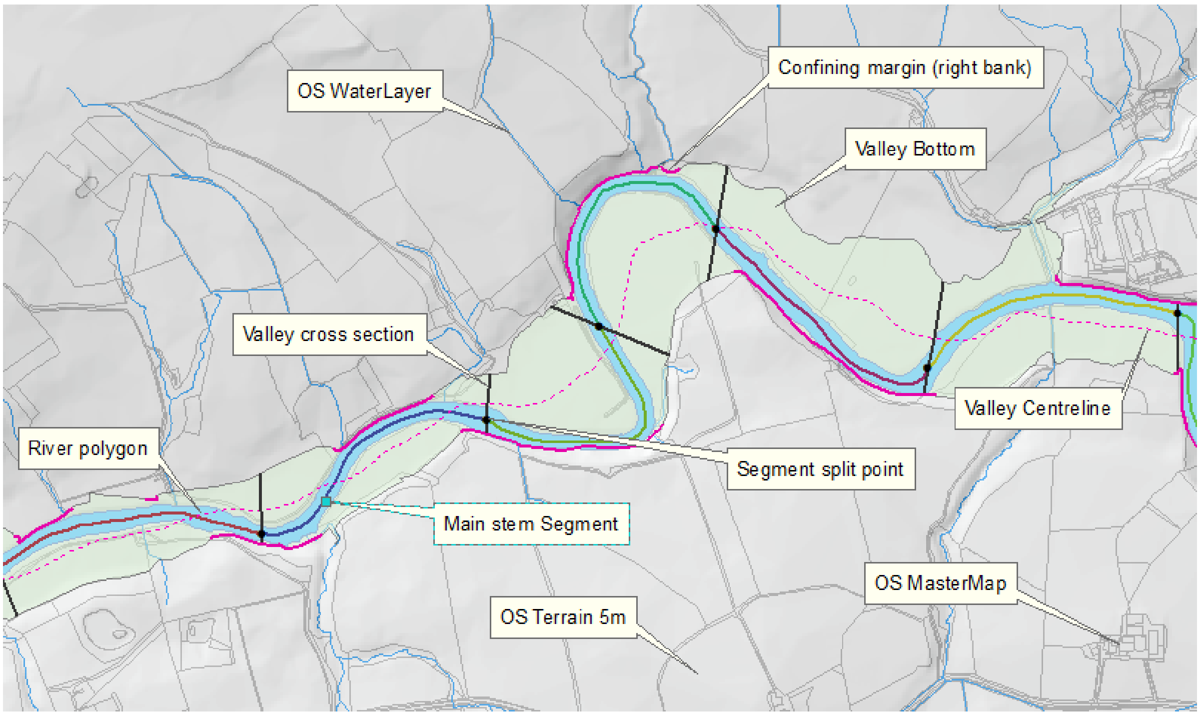


Figure A2 Ten layers of data and their relationship to one another

Only geology and landcover are not shown for purposes of clarity.

Details of the specific tools used to produce the measures can be found in the Help file, which is stored on github. To access the helpfile, load the helpfile on the C: directory; please follow guidance on the readme.txt file on: https://github.com/Hornbydd/ConfinementTool/blob/master/UC1476_Help

The code for the tools and processing within this project is included on:

https://github.com/Hornbydd/ConfinementTool and the source code for the confinement tool is available at http://confinement.riverscapes.xyz.

A6 Issues of scaling up to national levels

A6.1 Data preparation

Developing the processing needed to generate a national data set is difficult, but includes both preparing and processing the input data and redeveloping the tool for the UK situation and available data resources. The duration of the processing and model runs within the Derwent case study may give a false impression of how much preparation is required, as it is a ‘simple’ catchment.

The following sections identify the processing requirements for the river network lines and network polygons, the valley bottom, redevelopment of the tool and other processing challenges. A summary of the estimate processing and development time is provided and some conclusions on resource requirements and IP issues.

A6.1 The network (lines)

The primacy field in the OS WaterLayer was used to drop loops. It is defined as the ‘value indicating the relative importance of the WatercourseLink within any larger watercourse it is part of.’ Primacy 1 indicates the primary flow. For the Derwent, which has few drains or secondary channels, this is a simple and convenient way of creating a single threaded network.

If this logic is to be rolled out nationally and applied, for example to the River Frome in Dorset, the same processing steps would not always drop loops, as both sides of the loop have been coded up as the primary flow. Also, the flood plains are full of drains, which are primary flow (Figure A3).

Figure A3 Frome where primacy 1 has been selected

So, any data preparation logic needs to be appropriate for the type of catchment (high energy, semi-natural versus low energy, highly modified). An alternative is to improve the attribution within the OS WaterLayer, although that has not been considered here, but it would be a valuable addition to the quality of the OS WaterLayer.

Running this process across England is estimated to take at least 6 months. Assumptions and logic worked up for the Derwent are not likely to apply in all situations; different logics will require research and development.

A6.1 The network (polygons)

The Confinement Tool requires a channel polygon for input. The OS MasterMap topographic area can provide this, but it needs significant intervention. Where roads/bridges/weirs/other structures cross the channel, they are not classified as water (Figure A4), so when pulling out just the water polygons hundreds of gaps occur. This could easily equate to thousands of gaps in a large catchment, scaling up to millions for the whole country.

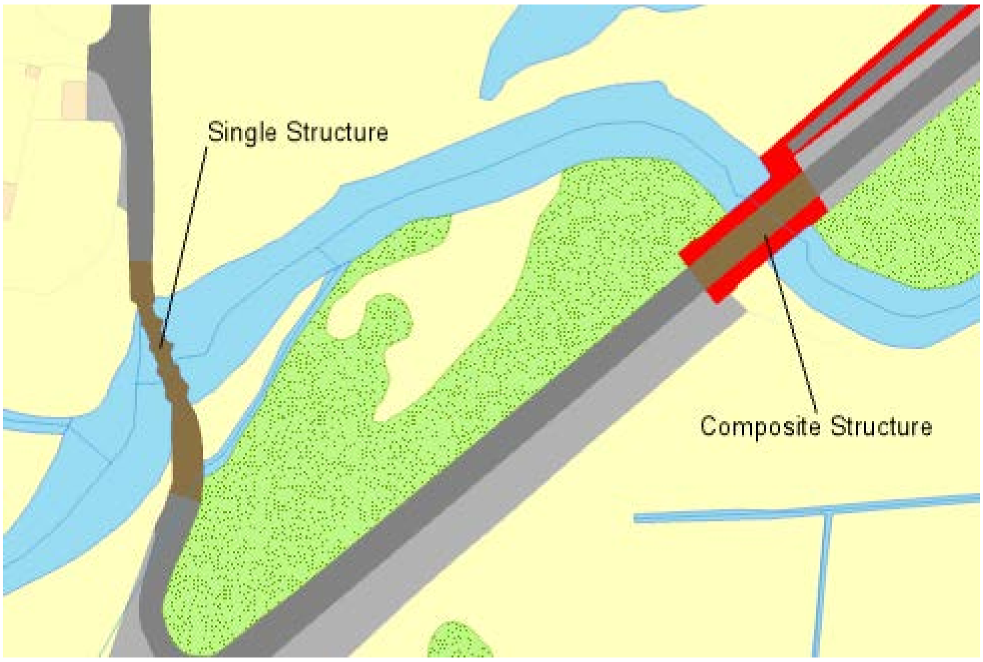


Figure A4 Single and composite structures when dropped from OS MasterMap will introduce gaps into the water polygons

GeoData has separately developed an FME python script to plug the gaps, but this was not run nationally for all channels (it was run across the Scottish river networks).

Running this across England is estimated to take around 2 to 4 months, assuming FME scripts don't need correcting significantly, with follow up editing of pathological cases.

A6.1 The valley bottom (Flood zone 2)

The flood zone 2 map is modelled data with many internal boundaries. If left in the data set they would generate false positive confinement margins, so the flood map needs cleaning up by removing internal boundaries. These boundaries are different to the internal boundaries created by holes (topographic highs in the flood plain, for example, an embankment). Logic was developed for the Derwent case study to drop insignificant holes. This may be appropriate for all catchments, but remains uncertain. Local knowledge needs to be integrated (as happened in the case of the Derwent) to add in any additional constraints. Developing national coverage would not include these local features and therefore would probably miss some main constrictions in the flood plain.

Running this across England is estimated to take around 2 to 3 weeks to do the initial dissolve and then drop holes.

A6.2 Other processing

Segmentation becomes relatively trivial if the network is reduced to a single thread and encoded with Hack order. Rolling out a segmented network for England would be relatively quick if the centreline network work were simplified. A single main channel would need to be identified (to fulfil the confinement logic) and drop off all in-flood plain ditches; considering the River Frome example when assessing the difficulty of this problem. There are also locations where the underlying logic may not apply (such as the drainage network in Norfolk). However, confinement may not apply or be relevant to geomorphic change in these areas.

Using the end points of centreline segments as starting points to partition the flood plain currently relies on the existence of a valley centreline to orientate the cross sections. The valley centreline is a challenging data set to create and has not yet dealt with the issue of tributary junctions of incoming streams with their own valley centreline within the case study. Therefore, there still remains some degree of uncertainty, and testing methods further may be a better first step before applying them nationally. It may be feasible to generate a cruder, less representative flood plain partition that would still yield suitable data.

Significant research and development are required if these stages are to be automated, but they are relevant to a wide range of applications.

A7 Developing a tool for national deployment

The Riverscape Confinement Tool has technical issues when applied to complex whole catchments, as happened during testing in the River Kent catchment. The confinement tool was originally designed around simpler network scenarios and did not attempt to fix a variety of topological issues (for example, segments collapsing to null geometry). This issue is mainly due to the way the tool was developed, using existing tools and processing at a data set level. This type of approach cannot deal with the complexity that comes with OS MasterMap WaterLayer, and may struggle with complex river networks and anastomosed, branching or braided channels.

The concepts of the confinement tool are appropriate, but they were built for US data sets and therefore may be less effective in the UK situation or where the complexity of the network is retained. Using the tool nationally would mean having to implement it again, making the model suitable for the available UK data sets. The development environment could use several computer languages, but the choice would need to consider the runtimes. On this basis, it is recommended that it is developed in a Visual Basic .net environment.

A fundamental assumption of the tool is that it is dealing with one channel in the flood plain. There is a significant challenge where there are multi-channel environments and where the network also includes drains and ditches, including those that are catch drains and carriers which often run along the valley margin. The OS MasterMap WaterLayer coding may also not distinguish a single main channel where more than one channel is coded as the primary flow (for example, the River Frome scenario). It may be that this confinement processing does not need to happen in these situations, as they may inherently not be confined. If this is the case, within national processing it is necessary to identify the catchments (or parts of the catchment) where this would be excluded.

OS MasterMap is a very large and complex data set and as such there are likely to be issues that have not been considered or encountered within the case study. For this reason, it is likely to take at least 2 to 3 months to develop the tool, rebuilding the code, testing and documenting, assuming the issues above have been resolved.

A8 Development and processing timescales

It is clear from the case study that both research and development are needed to implement the tool nationally, whether that is a single activity across the whole of England or provided as a tool and data sets to run at a catchment scale. Overall, the research and development time for a national roll out of the applications would be around 14 to 18 months.

This research and development work would need a fluvial geomorphologist (to validate the logic/conceptual models) and a GIS application developer who has extensive experience of working with the UK river network and related catchment level data, together with coding skills in VB.net/Python and FME, and advanced GIS spatial processing skills.

IPR issues in generating the data are covered by the licences of the OS MasterMap and OS WaterLayer data and should confirm the rights to the derived data sets. The re-development of the tool (as with the current development) is proposed as Free Open Source Software (FOSS) released under an appropriate open source licence.

Appendix B: Deriving geomorphic change for the River Derwent case study

The Derwent drainage basin, Cumbria (North West England) has experienced a series of recent extreme floods and several historical high magnitude floods (Miller and others, 2013). The catchment has been subject to extreme flooding in recent years, with significant events in December 2015, November 2009 and December 2005 (Barker and others, 2016, Parry and others, 2016). For each of these events, warm moist south-westerly airstreams associated with deep Atlantic depressions tracking north-eastwards affected the UK (Barker and others, 2016). The catchment landscape reflects the impacts of repeated glaciation, resulting in steep slopes and glacial deposits. Valley form is U-shaped, with a suite of glacial and holocene terraces that confine the existing river channel. The 24 km study reach lies downstream of Lake Bassenthwaite, which removes all coarse (>1 mm) sediment supplied from the upstream catchment. Therefore, any geomorphic response in the River Derwent trunk stream will be caused by the activation of local sediment stores plus the addition of sediment from tributary inputs, notably the Cocker (131 km^2), Lostrigg (13 km^2) and Marron (53 km^2).

The Environment Agency provided a digital elevation model (DEM) at 2 m resolution of the study site, generated from an airborne laser altimetry (LiDAR) survey flown in 1998 and April and May 2009. The majority of the data was from 1998 and had a vertical root mean square error (RMSE) of approximately 0.25 m (Wong and others, 2014). Data to quantify the river channel geometry and bed material grain size of the River Derwent were also available. Some 234 and 191 channel cross sections were surveyed for a 32 km reach of the River Derwent in 1998 and 2010 respectively. The Environment Agency provided the 1998 data set, which was based on a number of Section 105 cross section surveys and repeat cross sections within the town of Cockermouth. The 1998 cross sections were located at a mean spacing of 124 m to reflect channel morphological complexity. On the section of channel upstream of the main road bridge at Cockermouth, the cross sections were given a mean spacing of around 23.15 m, reflecting the importance of the confluence of the Derwent and Cocker. The 2010 data was based on cross sections surveyed by the Environment Agency in December 2009 at a mean spacing of 151 m, from Workington to immediately upstream of Cockermouth. In addition, 127 repeat cross sections were surveyed for the whole river in May and August 2010 by this study. The 2010 cross sections were taken at locations close to those made in 1998, of which 93 could be paired as they were within 10 m of each other. The number of survey points per cross section for the 1998 survey was 31, with a mean cross section spacing of 1.09 m between adjacent survey points. The bed elevations range from 4.20 m to 67.44 m (above sea level) and the average width of the river is 34.97 m.

Due to the fact that there were 5 major flood events between 2003 and 2008, the 1998 DEM was updated and modified to provide a better representation of topography before the 2009 flood event. The 1998 DEM was built from a combination of data sets: 1998 LiDAR 2 m DEM, 1998 cross section survey, 2005 repeat cross section survey for the reach through the town of Cockermouth, and bank outlines derived from the latest aerial photographs (1:3,000) taken in 2004. Masks of the flood plain extent and wetted channel were created from the LiDAR 2 m DEM and 1998 colour aerial photography. These were used to clip the 1998 LiDAR DEM. Where bank migration had occurred between 1998 and 2004, the cross section data were moved to the position of the 2004 bankline. This affected less than 5% of the total cross sections surveyed. In the area of wetted channel, 1998 (adjusted to 2004 banklines) and post-2005 flood cross sections were interpolated to generate cross sections at 5 m spacing throughout the whole channel using the method of Merwade and others (2008). Comparison between surveyed cross section elevation and those derived from the interpolation resulted in a root mean square error (RMSE) of 0.235 m, with no evidence of bias towards incision or aggradation. The cross section nodes were exported as a point file and combined with the LiDAR 2 m DEM data within the 2004 bankline mask. The resulting point file was converted into a 2 m raster DEM using the ArcMap 10.1 raster interpolation and the inverse distance weighted algorithm. The 2004 banklines were used as 3D breaklines (Wheaton and others, 2010). The resulting DEM was integrated into the LiDAR 2 m DEM to create a 2 m DEM for the wetted and non-wetted valley floor for pre- and post-2009 flood.

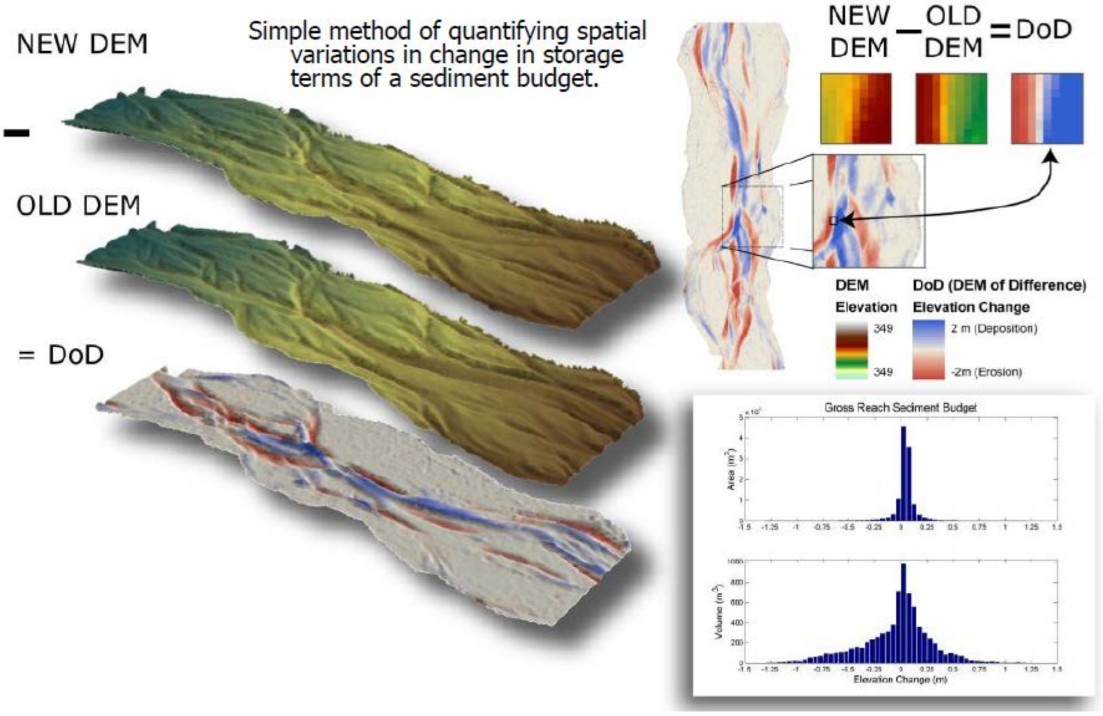


Figure B1 Methodological process for generating a sediment budget by differencing repeat digital elevation models (DEM)

> *In the case of the River Derwent, the 2004 DEM was subtracted from the 2010 post Cumbrian flood DEM to create a DEM of Difference (DoD). An error mask was applied to the resulting data to screen out unacceptable levels of uncertainty in the topographic data, leaving only the changes where there was confidence. The result is a map of elevation changes for each grid cell making up the DoD, which when multiplied by the standard grid cell area gives volumes of topographic change – negative values denoting erosion and positive values deposition. These are then added together for each 500 m floodplain segment to give a measure of geomorphic effectiveness (after Wheaton and others, 2010).*

To generate the sediment budget, the methods detailed in Wheaton and others (2010) Figure B1 were adopted. Geomorphic change detection software (GCDv5 Wheaton and others, 2019) was applied to calculate the difference between sequential DEMs and to carry out a spatially variable uncertainty analysis to clearly distinguish areas of erosion and deposition. Error masks were created (for example, sand areas, flood plains areas) based on the error surfaces and applied probability thresholding at 95%. Bayesian updating was run using a spatial coherence filter (9x9cell moving window) with 60%:70% transform function (Wheaton and others, 2010). The error model was selected by comparing the resulting erosion:deposition with air photos and field observations of deposition and erosion taken just after the flood. The model represents the combination that produced the closest fit to the observed area of deposits. The magnitude of difference (vertical change in deposits) was also screened for and compared to field observations as a check that spurious depths of erosion or deposition were not being produced. Finally, the budget was constrained to only those areas of erosion and deposition observed in the field or mapped from post-flood air photography.

The volumetric change in storage is calculated by multiplying all ‘certain’ elevation changes in the DoD by the cell area and accounting separately for erosion and deposition areas. The methods are useful for establishing confidence that ‘real changes’ were reliably being distinguished from noise. More details of the methods are available in Wheaton and others (2010).

The resulting analysis provided a volumetric sediment budget for the whole River Derwent from Lake Bassenthwaite to Workington Weir (Figure B2a).

For the Storm Desmond floods of 2015, a different approach was adopted owing to a lack of repeat cross sections and piecemeal coverage of post flood LiDAR. Instead, all areas of sediment in channel and on the flood plain as well as the bank line were digitised. The differences the 2010 bank line and 2016 bank line were used to determine erosion from deposition. The result was an estimation of the areas of deposition and erosion for the same 24 km valley length as for the 2009 Cumbrian floods (Figure B2b).

To identify the magnitude of geomorphic change – the measure of flood effectiveness, the areas of erosion and deposition were added together for each 500 m flood plain segment for the events of 2009 and 2015 to generate a measure of total geomorphic change (Figure B2c). The benefit of using this measure of change is that it represents a consistent as well as event-specific response to extreme flooding. This allows it to identify segments that exhibit similar behaviour. This measure is used in subsequent MCA analysis.

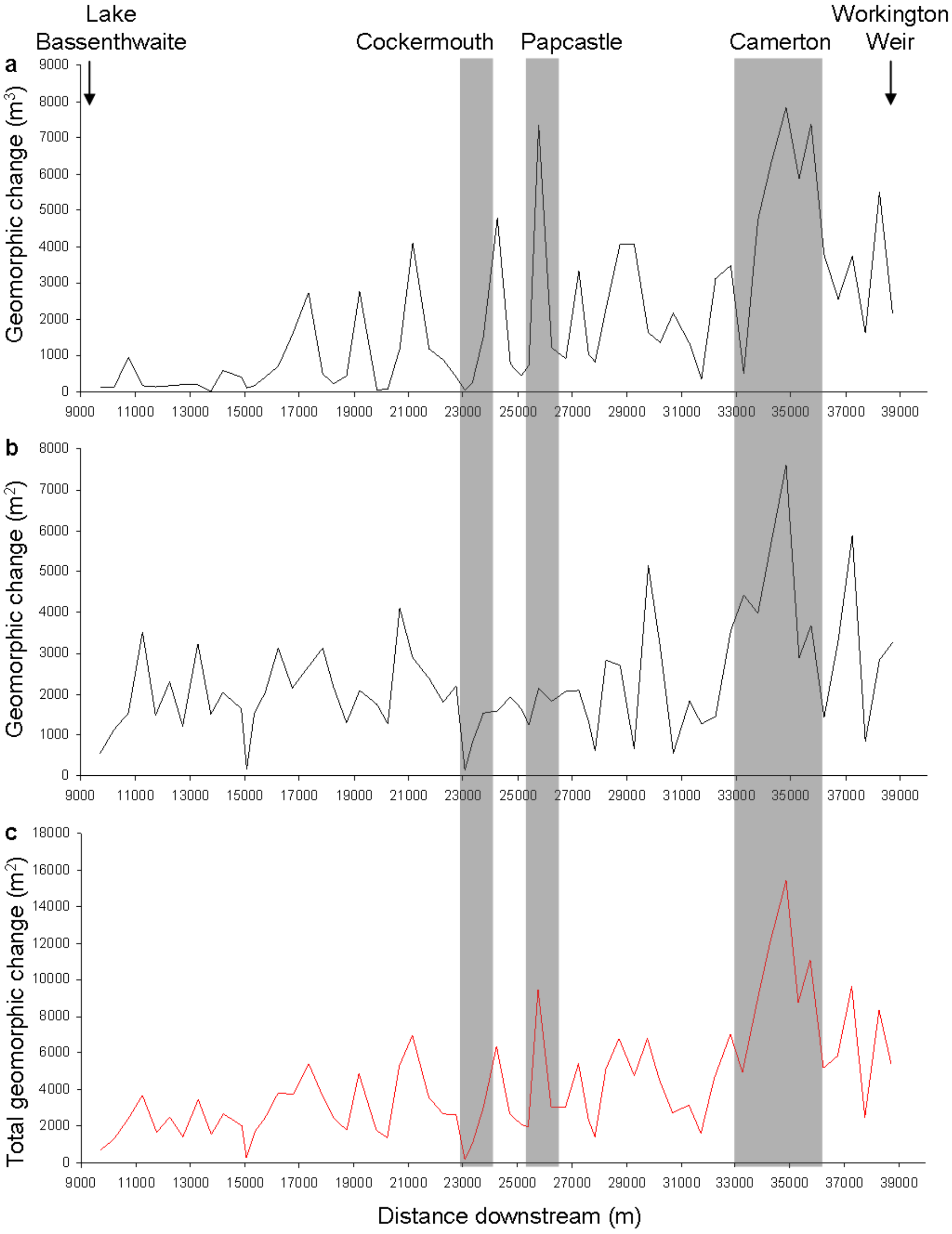


Figure B2 Measures of geomorphic change (effectiveness) for the River Derwent

a) Cumbrian floods 2009 gross (erosion plus deposition) volumetric sediment budget, b) Storm Desmond 2015 area of erosion plus deposition, c) Total geomorphic change for 2009 plus 2015 areas of erosion plus deposition. Note in 2015, flood flows were larger than 2009 upstream of Cockermouth, which results in larger geomorphic change in that reach in 2015.

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