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Understanding river channel sensitivity to geomorphological changes

Literature review and understanding factors that influence river channel change

FRS17183/R1

Flood and Coastal Erosion Risk Management Research and Development Programme

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Professor Doug Wilson
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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 aims 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 (this report, 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 (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)

A literature review has been carried out to summarise evidence of morphological and sedimentological impacts during flood flows; to investigate what factors influence the scale and route of morphological changes; and to suggest ways in which morphological changes impact flood hazard.

This is supported by a review of flood events, focusing on the 2005, 2007, 2008, 2009, and 2015 to 2016 events. The background cause of each flood event was examined, as well as the morphological channel change in response to the flood and any resulting flood impacts.

Data provided by the Environment Agency covered a variety of flood investigation reports, fluvial audits as well as online sources to support this review. Information was provided for the Kent and Wharfe catchments, as well as a wider range of catchments impacted by these flood events.

Main findings

From the review of literature and flood events, key factors were identified that can potentially influence the degree of sensitivity to morphological change during flood events.

These factors are summarised as follows:

Dominant factor:

- Channel confinement

    - Bedrock/valley confinement
    - Anthropogenic confinement (due to human activity):
        - flood plain infrastructure
        - in-channel structures
        - asset failure
        - channel modification

Other factors:

- Sediment supply and connectivity
- Large wood and riparian vegetation
- Magnitude, duration and sequencing of flows
- Channel maintenance
- Land use changes
- Channel slope (natural)

The dominant influencing factor of channel confinement is associated with natural confinement as well as past and current human interventions in the channel. In fact, nearly all of the examples cited in the review of flood generated adjustments involve human activity, which has significantly affected the river's capacity to adjust and led to irreversible changes. Human activity triggers, amplifies and distorts morphological responses to flood events. Based on the literature and flood report review, it is apparent that human rather than natural influences on river systems are often likely to have a more frequent or more pronounced impact on the sensitivity of channel response to flood events.

Using data sets to identify influencing factors

Data sets can be used (before modelling) to identify where influencing factors may lead to hotspots of sensitivity to change. A wide range of data sets was considered, including LiDAR, aerial imagery, Ordnance Survey mapping and Environment Agency flood risk management asset data. The literature and review of flood events revealed that influencing factors often have a greater impact when they occur together. Links between the factors were therefore explored when considering how existing, national data sets could be used.

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- the case studies of the River Caldew, River Derwent, Wooler Water, River Greta and River Wear were provided by Duncan Wishart.

Contents

List of tables and figures

1 Introduction

1.1 Background

We commissioned JBA Consulting in 2018 to conduct a research project entitled 'Channel sensitivity to morphological changes (in normal and extreme flood flows) and impact on future flooding'.

The frequency of floods has been projected to increase across England and Wales in the coming decades due to extreme weather events. We recognise that we need to understand more about where and when changes in geomorphological activity (erosion, deposition and transport) are likely, and how any resulting river channel changes could affect our estimation of flood hazard in the future. There is also uncertainty about the impact of extreme flooding on future geomorphological activity.

River channels change over time and this can alter flood risk. We need to better understand this and we may need tools and data to account for these changes in our flood risk assessments or operational activities. Climate change causing more extreme flooding more often is likely to make these issues more frequent in the future.

This commission has identified ways to understand geomorphological sensitivity of rivers in England and Wales and assess how future anticipated hydrological change in flow may change sediment load and channel behaviour. This has been achieved by testing a small number of approaches in trial catchments. Supported by a literature review and initial analysis, this project has built an evidence base to understand, within the context of recent flooding in the UK, what natural and human factors can influence or control channel changes. It has made an initial assessment of how these factors may affect flood risk. The project has demonstrated methods and analysis that could be widely used to inform flood risk management activities (for example, risk assessment modelling, channel maintenance plans, scheme design and maintenance plans, catchment restoration and implementing natural flood management, planning and permitting).

The project analysis and findings will help us to understand how to identify potential morphological change in river channels and how we may use this to inform a risk-based approach to flood management. This project is documented in 4 reports. This is report 1: Literature review and understanding factors that influence river channel change.

1.2 Report aims

This report summarises the work completed to carry out a literature review and to understand the factors that influence river channel change. The objectives are to:

- carry out a literature review to summarise evidence of morphological and sedimentological impacts during flood flow conditions. Specifically extract references to factors that can influence the scale and rate of morphological changes. Summarise theories of how this could impact flood hazard

- collate relevant and available data on the floods of 2005, 2007, 2008, 2009 and 2015 to 2016 and use the data to form case studies of morphological channel change and flood impacts. This information will be used to inform the significance of including influencing factors in any assessment/prediction of channel changes

- use the data and literature review to list key factors that could influence the scale of sensitivity, classifying the type of change (sedimentation, erosion) and relative degree of impact change in channel capacity and discharge). Influencing factors could include typology, channel bed type, land use, soil type, asset failures, landslides, presence of road and rail infrastructure over or close to channels

2 Literature review

2.1 River sensitivity to morphological change

2.1.1 Definition

River sensitivity is defined as “a system response characteristic that describes the severity of a response to a disturbance, relative to the magnitude of the disturbance force” (Schumm 1991; Downs and Gregory, 2004 in Fryirs 2017). There are 3 different aspects that allow us to assess river sensitivity to a disturbance event, as defined by Downs and Gregory (1993, 2004).

Firstly, how possible is it for a river to change? This relates to the balance of driving and resisting forces acting in a fluvial system. Where a disturbance (driving force) exceeds the resisting forces, morphological change is likely to occur as the river planform adjusts in response to the attributes associated with the disturbance, for example a river channel may widen in response to increased discharge (and associated increased stream power) during a flood event.

Secondly, how probable is it for a river to change significantly? This describes how close the fluvial system is to particular thresholds, which determine the type of changes that may occur. For example, previous disturbance events may have triggered morphological responses which cause a river reach to be more sensitive to future morphological change.

Finally, is the river easily able to recover? This describes whether change is reversible and, if so, how long the system takes to recover or relax following a disturbance event, relative to the recurrence interval of the disturbance. There are many definitions of river sensitivity in literature, some more complex than others. Although the definitions presented above are some of the more comprehensible, in practice assessing river sensitivity is complicated, due to the complexity, nested nature and non-linear response of fluvial systems to disturbances (Fryirs, 2017).

Sensitivity can be investigated over space (spatial scale) and time (temporal scale). (Figure 2-1). In terms of space, river sensitivity can be measured at a landform (geomorphic) reach and catchment scale. Sensitivity at the geomorphic scale is determined by textural and geometric sensitivity. Textural sensitivity describes the sedimentological composition of a geomorphic unit, which determines the ease at which it may be reworked or entrained (for example, Hjulström, 1935). Geometric sensitivity describes the process by which the form of a unit aligns with the energy specification of a system. The probability of a reach to change is ultimately determined by its morphological configuration at a geomorphic unit scale. At reach scale, the morphology and, therefore, type of river adjusts to the balance of hydrological, geological and biological forces and interactions between them, which occur at a catchment scale.

Reach-scale sensitivity will be the main focus in this report, but due to the connections between different scales (Figure 2.1, Figure 2.2), understanding the wider processes used to determine reach-scale sensitivity will mean understanding reaches at a geomorphic unit and catchment scale.

Within this report, river sensitivity will also be investigated over time, namely in terms of the magnitude-frequency-duration of the flood event, its direct morphological impact and indirect influence on the response of the river to future disturbance events (Figure 2.1).

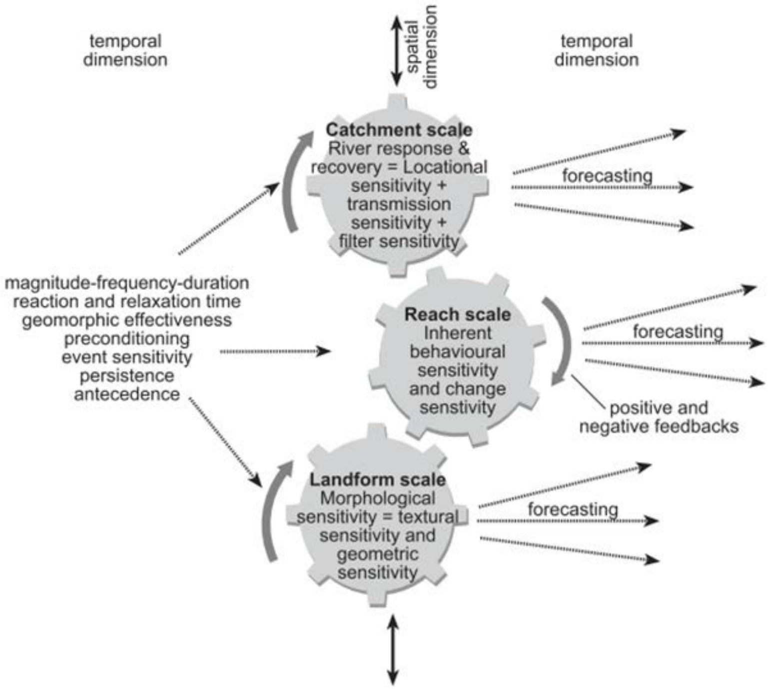


Figure 2-1 Conceptual framework for assessing river sensitivity over space and time, from Fryirs (2017)

2.1.2 River behaviour versus change

Different river types are produced as a result of water, sediment and biological interactions. The morphology and sediment dynamics of a reach depend on the type, size and frequency of sediment and water delivered from upstream reaches/slopes, as well as the geological resistance of the channel, capacity of the channel to transport the sediment and water to downstream reaches and biological influences on the channel (Montgomery and Buffington, 1993). All of these factors have varying amounts of influence throughout the catchment, which causes spatial variation in river morphologies.

When investigating reach-scale sensitivity, it is important to differentiate between river behaviour and change (Brierley and Fryirs, 2016). River behaviour describes constant morphological adjustments within a channel type as configurations of geomorphic units are moulded and reworked, while flux boundary conditions remain similar. Over timescales relevant to river and flood risk management, different channel types have different capacities to adjust. For example, the stream in a bedrock gorge is naturally unable to adjust laterally, with minimal vertical adjustments, while a lowland, braided river is naturally free to adjust, both vertically and laterally. In fact, the braided river is adjusting all the time, although its morphology may not change significantly through time, just like that of the stream in the gorge. The difference is that the morphology of the braided river is in a state of meta-stable dynamic equilibrium, while the stream in the gorge is in static equilibrium (Schumm, 1973). Either equilibrium condition is breached when a disturbance alters the balance of driving and resisting forces enough to cause the river to change into a different type, with different behavioural attributes. This change may occur suddenly and catastrophically, as a result of a high magnitude event, or it may occur in response to a low magnitude event if the system is close to a threshold (Church, 2002).

There has been much discussion concerning the factors that influence the types, extents and rates of morphological change, with some studies agreeing that hydraulic variables such as stream power are the most influential.

Stream power, a function of discharge and channel gradient, has been used in many studies as an indicator of the energy a river has to perform geomorphic work, and it can be used to calculate thresholds for channel stability (Bizzi and Lerner, 2015). Stream behaviour and evolution occur due to continuous interactions between driving forces (hydrology) and resisting forces (geology, biology), but if the relative influences of these high-level drivers of river process and form change significantly, the balance between unit stream power and resistance is perturbed, which may cause the river type to change (Castro and Thorne, 2019).

Brierley and Fryirs (2005, 2016) present the river evolution diagram as a way of predicting future morphological change within a given fluvial system, based on stream power values (Figure 2.2). The dashed lines in Figure 2.2 represent controls imposed by geology (such as upstream catchment area, slope and valley confinement), which set boundaries on the range of total stream power values that do not change over time, and define the potential range of variability. This range bounds the types of channel morphologies that are able to form in that particular catchment context and valley setting. An inner band within that outer band reflects how the river behaves through minor adjustments to the channel and flood plain that occur in response to normal variability in stream power (that is, through water, sediment and vegetation interactions), defining the ‘expected capacity for adjustment’. The pathway of adjustment within the expected capacity for adjustment reflects river behaviour according to a certain river type, which will fluctuate over time, dependent on prevailing influences of geology, hydrology and biology, and the nature of disturbance events. During and following disturbance, the amplitude and trajectory of the pathway of adjustment will be very different for different river types.

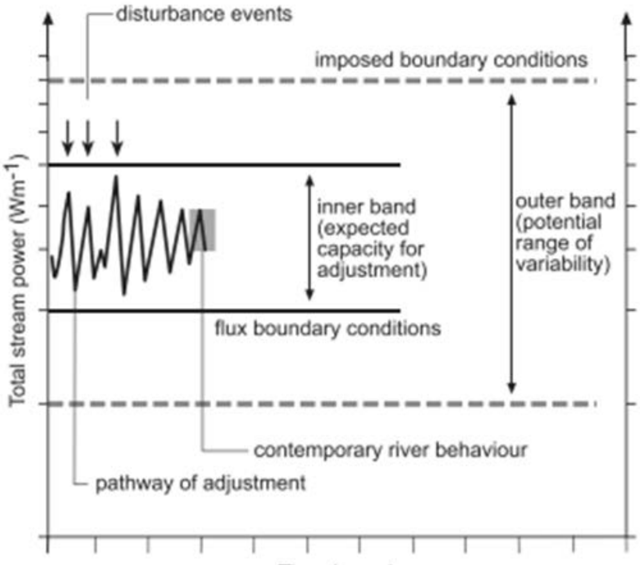


Figure 2-2 Basic river evolution diagram, from Brierley and Fryirs (2016)

Figure 2.3 uses the river evolution diagram to demonstrate the response of a river to disturbance events. An initial disturbance event may cause behavioural changes in a fluvial system that do not amount to a change in river type (shift from zone A to zone B). These changes may expand the expected capacity for adjustment (Figure 2.3a), or contract it (Figure 2.3b). Structural and functional attributes of the river reach may be altered, but key defining attributes of the river type are maintained and, essentially, these behavioural adjustments are reversible. However, the initial disturbance event may impact the way in which the river responds to subsequent disturbances, by moving the river closer to or further away from a threshold of significant change, which increases or reduces its potential to change, respectively. In response to a subsequent disturbance, river change occurs, reflected by a shift in the position of the inner band from zones A or B, to zone C. This change is irreversible, as the river has changed its geomorphic type and is now in a different process domain, with altered stream processes, morphologies and capacity for adjustment.

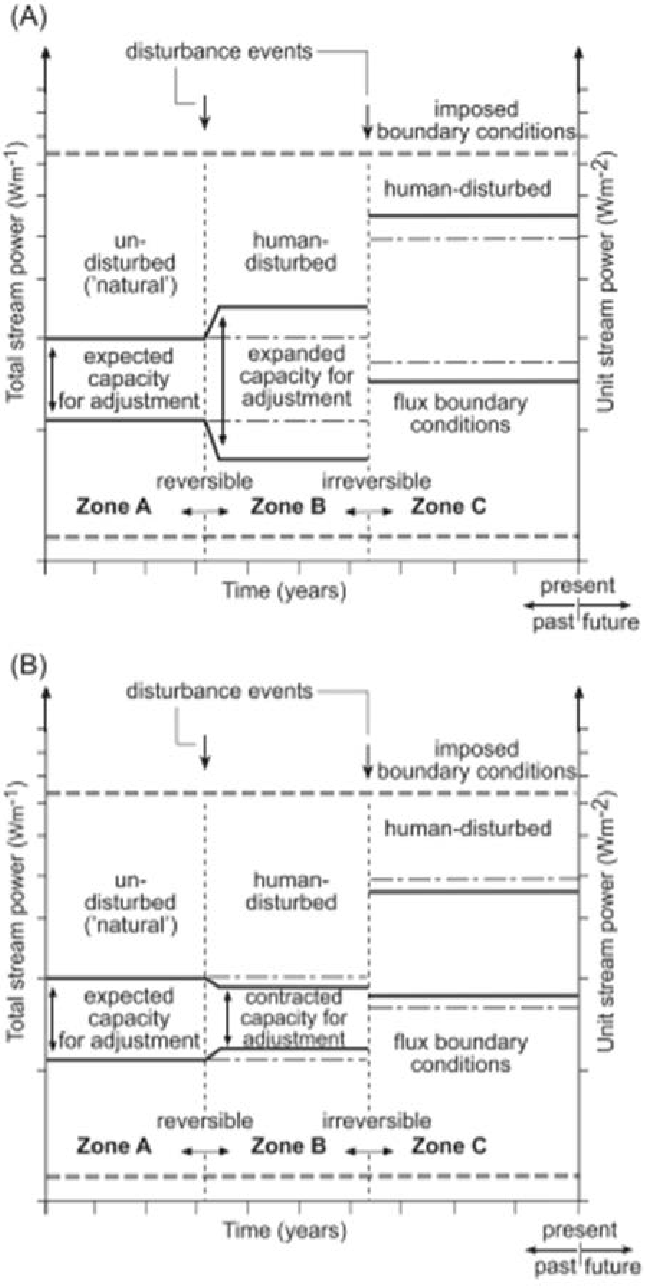


Figure 2-3 River evolution diagram showing river response to disturbance events (a) disturbance events that expand the capacity for adjustment, (b) disturbance events that contract the capacity for adjustment, from Brierley and Fryirs (2016)

2.2 Factors influencing the extent and path of morphological change

Brierley and Fryir’s river evolution diagram shows that morphological changes can occur gradually, as a result of cumulative evolutionary adjustments, suddenly, in response to a high magnitude event, or in response to a lower magnitude event if the system was close to a threshold before the trigger event (Church, 2002). It is clear from the river evolution diagram that river morphology is highly dependent on (a) imposed boundary conditions (geology), (b) flux boundary conditions (interactions between water, sediment and biology) and the overriding factor of (c) human modifications. A change in these boundary conditions drives river behaviour and may cause a change in river type. Geological controls on catchment and valley relief, together with climatic controls on discharge and biology, drive the supplies of energy and sediment available to a river, which, in turn, determine river morphology and type. The fluvial system is naturally variable, but its behaviour and propensity for change may be impacted by past and current human modifications, giving a ‘historical range of variability’. The boundaries imposed by geology, stream power, sediment supply, biology and human modifications set the range of river types that is likely to occur at a given point in time and space, as well as determining the type, extent and rate of response to disturbance events such as floods (Fryirs and others, 2009).

Castro and Thorne (2019) present the stream evolution triangle, which visualises how stream morphology and evolution are governed by the relative influences of geology (erosion resistance), hydrology (stream power) and biology (biotic interaction) (Figure 2.4). Stream types (for example, Schumm (1985) in Figure 2.4) can be plotted within the triangle, with stream types predominantly governed by one driver located close to that corner. When there is a change in the balance of high level drivers, the plotting position of the river changes, representing a shift in process domain. For example, a large flood event would shift a river’s plotting position towards the hydrology corner. However, following the flood, the plotting position continues to change during post-disturbance evolution, usually shifting away from the hydrology corner as system forms and processes recover. The stream evolution triangle can be used alongside the river evolution diagram to identify the main factors and drivers influencing the type, rate and path of morphological change in response to flood events and during post-disturbance behaviour, change and evolution.

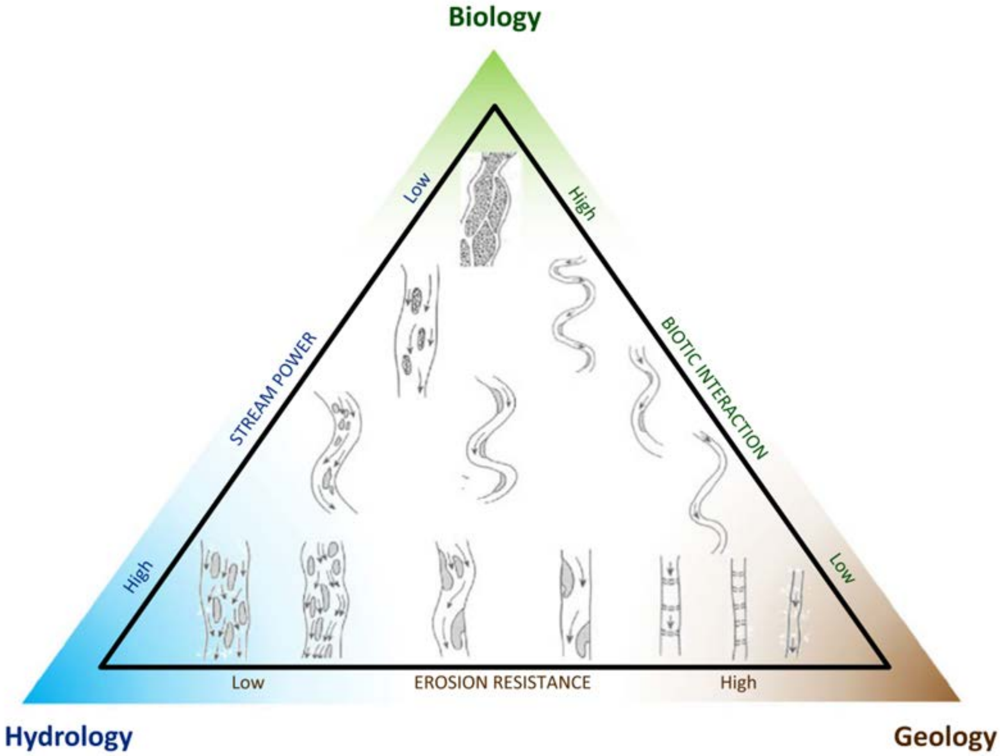


Figure 2-4 Stream evolution triangle with the planform patterns defined by Schumm (1985) used to illustrate typical morphologies that might be expected in different process domains within the triangle, from Castro and Thorne (2019)

2.2.1 The 'outer band' of the stream evolution diagram

Geological controls determine the outer band of imposed boundary conditions in Brierley and Fryir's river evolution diagram, 'setting limits' on the potential range of variability in which the river can adjust and change in response to flood events. In the stream evolution triangle (Castro and Thorne, 2019), geology is a resisting driver of river processes, forms and change, as resistant boundary materials (for example, bedrock or strongly cohesive sediments) reduce the potential for lateral and vertical erosion and therefore channel adjustments during flood events (Figure 2.5). Rivers plotting close to the geology corner (that is, source reaches, bedrock/colluvial, confined) are resistant to morphological change, often even in the face of extreme flood events, with morphologies that persist over human timescales (Castro and Thorne, 2019).

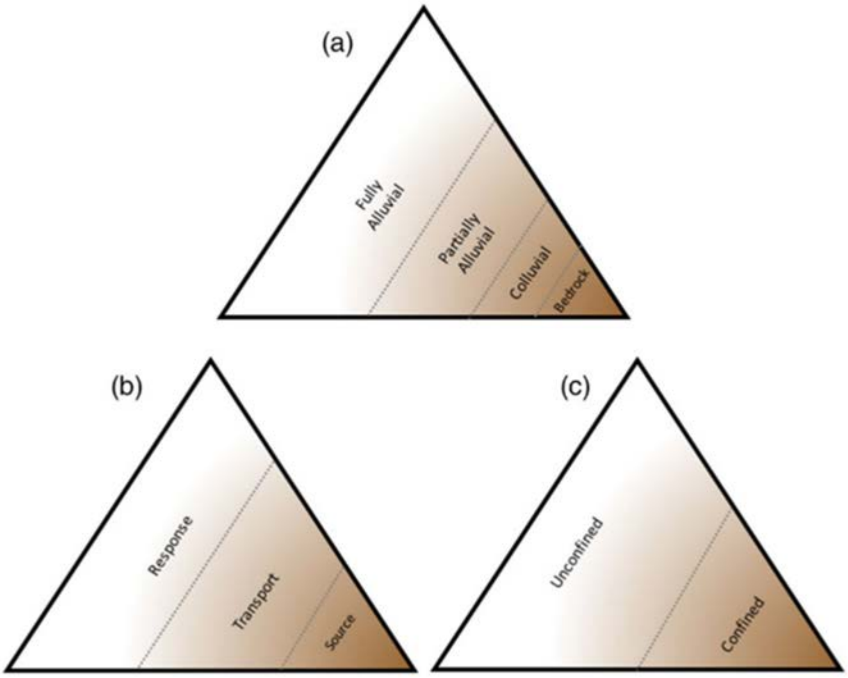


Figure 2-5 The decreasing influence of geological factors with distance from the 'geology' corner in the stream evolution triangle, from Castro and Thorne (2019)

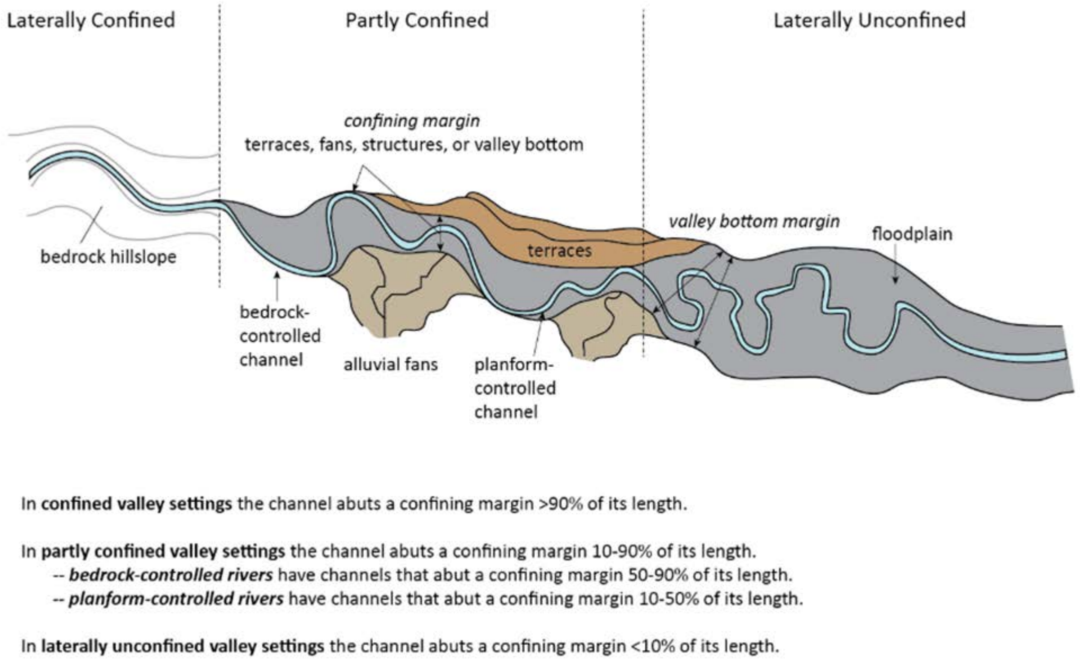
Brierley (2010) refers to 'geologic memory' as a term to represent previous influences on relief, erodibility, erosivity and accommodation space. From the outset, landscape setting can cause variations in catchment response to flood events. Lithology within the catchment determines the erodibility of the boundary materials and the potential for a channel to adjust or change in response to increased discharge or sediment supply. Variations in lithology, both within and between catchments, determine key factors such as topography, catchment permeability and vegetative cover (Baker, 1977). All of these factors influence overland flow, which, if concentrated, can produce intense flood peaks in parts of the catchment.

Topography also dictates the valley gradient, which influences stream power and the erosivity (shear stress generated) of a flood event. The steeper the slope, the higher the stream power, which increases the shear stress in the channel and on the flood plain, heightening the erosivity of the flood event. However, the morphological response of the channel depends on the erodibility of the bed and banks in relation to the erosivity of the event. For example, a bedrock channel is resistant to erosion and is therefore unlikely to significantly adjust laterally or vertically, even in response to a high magnitude flood. Similarly, stream power also determines the potential for a river to transport sediment. Larger material is only entrained during higher velocity flows, while fine material may be carried in suspension even during low flows. These concepts will be further developed in this and following sections.

Buffington and Montgomery (1993, 1997) note that there is a large variation in the type and magnitude of channel response between different locations in the drainage network. In many conceptual models, the upper reaches within the catchment are labelled 'source' reaches – this is where the channels are mainly non-alluvial and resistant lithologies limit the erosion of the channel bed and banks during flood events. In these reaches, rock and hillslope colluvium can be readily supplied to the channel from adjacent hillslopes, as sediment is easily entrained from steep, confining valley sides in some locations. As these reaches are energetic, the rate of sediment transport through them is determined by the sediment supply from the bed, banks or surrounding landscape during high magnitude flood events. That is, their bed material loads are supply limited. Mid-catchment reaches broadly form a zone of transition between higher-energy upland reaches to lower-energy lowland reaches. But the actual pattern in a given river system is usually not a simple picture of reducing energy with distance; instead, there will be transport reaches and depositional reaches back to back in this ‘middle’ zone. These reaches are generally more sensitive to disturbance than the upstream source reaches. Channels lower in the catchment are often labelled ‘response’ reaches – these are low gradient, dominantly alluvial (though they may abut valley sides in some locations), and sensitive to disturbance. Lower stream powers cause these reaches to be transport-limited and dominated by depositional processes. Stream energy is lowered by wide valleys and low slopes; therefore, sediment sinks on the flood plain tend not to be reworked (Church, 2002).

Valley width and confinement are a key control on the morphological response of streams to flood events. Levels of confinement differ throughout the drainage network, with a general downstream reduction in confinement (Figure 2.6). However, human channel modifications may cause a naturally unconfined channel to behave like a channel in a confined setting (see section 2.2.4). In confined valley settings, the channel abuts a confining margin for over 90% of its length (Fryirs and others, 2016). Flood plain does not border the channel edge, apart from in brief, irregular pockets. Rivers in confined valley settings generally have low capacity to adjust in response to flood events, as narrow bedrock margins are resistant to erosion (O’Brien and Wheaton, 2015). As can be seen in Figure 2.7, a river in a confined valley setting can vertically erode its channel bed, but rates of change are much lower than in an alluvial setting. In partly confined valley settings, the river meanders between alternate valley walls, with larger pockets of flood plain contained between meanders. The channel will abut the valley wall for 10 to 90% of its length, and the morphology of the river will reflect its position in relation to the confining margin (Fryirs and others, 2016). In these reaches, the confining margin may be bedrock, but also secondary features such as terraces or fans. These rivers generally have moderate potential for morphological adjustment to flood events, due to the reduction in the length of channel margin that is confined, but also as confining features are generally more erodible than bedrock (O’Brien and Wheaton, 2015).

In laterally unconfined valley settings, the channel will only abut confining margins for less than 10% of its length and therefore it has the potential to adjust vertically and laterally across the flood plain (Figure 2.7). These reaches have high adjustment potential (O’Brien and Wheaton, 2015). However, in a laterally unconfined setting the lateral spreading of overbank flows limits the depth of flow and associated boundary shear stress to that caused by bankfull flows, which reduces the impact of peak discharges on channel morphology. Conversely, in narrow, confined valley settings, discharges greater than bankfull will generate much higher stream powers and shear stresses (Miller, 1995). Following a low frequency, high magnitude event in January 2011, Thompson and Croke (2013) investigated and compared morphological response in confined and unconfined settings in the Lockyer Valley, South East Queensland. In the confined reach, peak flood power was 2 to 3 times higher than the unconfined reach. The morphological response in the confined reach was net erosional, with channel benches and microchannel banks stripped, causing channel widening. In the unconfined reach, 70% of the sediment exported from upstream was deposited on the benches and flood plains. These interactions between geology and hydrology will be explored further in section 2.2.2.



In **confined valley settings** the channel abuts a confining margin >90% of its length.

In **partly confined valley settings** the channel abuts a confining margin 10-90% of its length.
  -- ***bedrock-controlled rivers*** have channels that abut a confining margin 50-90% of its length.
  -- ***planform-controlled rivers*** have channels that abut a confining margin 10-50% of its length.

In **laterally unconfined valley settings** the channel abuts a confining margin <10% of its length.

Figure 2-6 Conceptual figure of confinement within a catchment. Grey shading indicated flood plain, from O'Brien and Wheaton (2015)

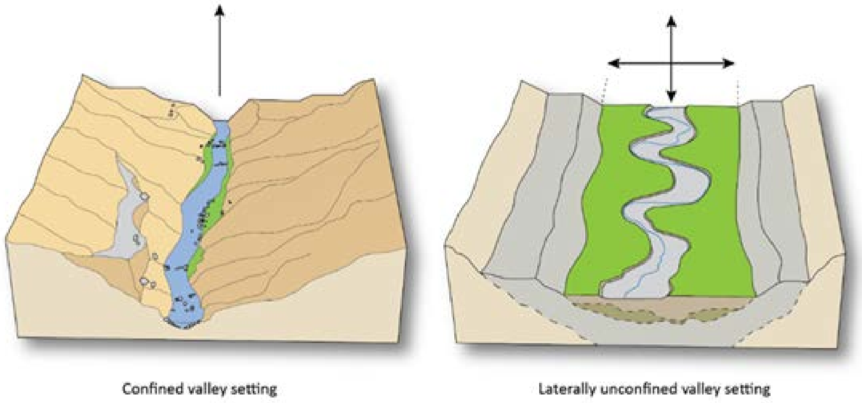


Figure 2-7 Ability of a river to adjust in a confined valley setting and laterally unconfined setting. Green shading indicated flood plain, from O'Brien and Wheaton (2015)

2.2.2 The inner band of the river evolution diagram

Referring back to the river evolution diagram (section 2.1.2; Brierley and Fryirs, 2016), geological controls set the outer band of imposed boundary conditions, which limit the total stream power in a given setting. Within this outer band there is also an inner band of flux boundary conditions, giving the range of unit stream power conditions for a river of a certain type and determining the 'expected capacity for adjustment'. This inner band reflects how the channel behaves - adjusting its form to variability in flux boundary conditions (that is, interactions between flow, sediment and resistance factors), which change over time. If the balance of driving and resistance factors in the flux boundary conditions alters significantly, the expected range of unit stream power values (expected capacity for adjustment) adjust and the river morphology is liable to change. The following section will provide an overview of some of the factors and interactions that control the ‘expected capacity for adjustment’ in response to flood events.

Magnitude, duration and sequencing of flows

Hydrology is a driver of morphological change as all aspects of the flow regime have an impact on river morphology, including flow frequency, sequencing, magnitude and duration (Soar and Thorne, 2011). In the frame of geological setting, the discharge generated during a flood event determines the capacity of the river to perform geomorphic work (Bizzi and Lerner, 2015). However, it is not discharge alone that determines flood effectiveness, rather it is the discharge sequence and magnitude driven by climate and landscape topography, translated into geomorphic work by confinement, slope and channel morphology and roughness. Morphological responses for a given event may therefore differ between reaches and catchments, depending on a range of physical controls within the catchment, such as soil permeability, rock type, drainage density, vegetative cover and hillslope steepness (Baker, 1977). These physical factors also control overland flow, which, if concentrated, can produce intense flood peaks.

The relative morphological importance of small but regular flow events over large, infrequent events depends on channel type. Wolman and Miller (1960) suggest that the features of many alluvial rivers are shaped by flows at or near bankfull. These events occur generally once every year or two, rather than catastrophic events which generally recur once in 50 or 100 years. Surian and others (2009) investigated the morphological response of a gravel-bed river to flood events of different magnitude, with recurrence intervals from 1.1 to 12 years. The results showed that small floods (20 to 50% of the bankfull or barfull discharge, recurring less than once a year) can be considered formative for the (low flow) channels. Larger floods, but still recurring less than every 5 years, are capable of transporting gravel on high bars and initiating morphological change of in-channel islands. In another gravel bed river in Italy, flows well below bankfull were observed to cause morphological change, although this was limited to a few active branches (Bertoldi and others, 2010).

Wolman and Miller (1960) state that “the rare and infrequent events become increasingly important as the threshold stress (competence) required to move the available masses of material increases.” In upland areas, where large material is present, significant channel-reforming floods only occur in response to extremely localised high rainfall. This type of event is rare, occurring often only once in 30 to 50 years. During these events, river catchments that have been stable for decades may suddenly and significantly be modified by major flood events. For example, until 2001, no significant morphological change had been documented in creeks in the Hungry Mother Basin, Virginia (USA) since 1985. A flood with a 5% annual exceedance probability occurred in 2001 and caused significant bank erosion and coarse sediment transport, which had not been observed for decades (Phillips, 2002). In a paper by Milan (2012), photographs of the Thinhope Burn catchment (Cumbria, UK) in 2003 showed a system that had been stable for some time, with a narrow, single thread channel flowing between densely vegetated channel terraces. In 2007, the landscape was significantly changed when a large flood caused erosion and redeposition of sediment stored in terraces and berms. 279 m^3 of sediment was eroded and 339 m^3 of deposition was calculated to occur in the reach. During the 2007 flood event, 2,125 m^3 of sediment was eroded and 5,202 m^3 of sediment was deposited. The River Derwent (Cumbria, UK) had been stable for decades before it was suddenly modified in 2009 by a flood well in excess of the 1% annual exceedance probability flow (Jacobs, 2010). The flood caused significant channel erosion, mainly bank retreat, and flood plain sediment deposition.

As flow convergence occurs lower down in the drainage network, higher flows occur more often downstream. However, moving down through the catchment, the force required to transport materials is lower than that upstream, due to downstream reduction in sediment size. Therefore, channel forming flows often occur at a higher annual exceedance probability compared to those upstream (Church, 2002).

If large floods occur consecutively, the impacts of the later flood may be increased. As Ward (1978, p.57, as quoted by Morche and others, 2007, p.17) states, "To some extent the geomorphological importance of catastrophic events will depend on their distribution in time. Although they are, by definition, rare they are not necessarily evenly spaced through time and it seems likely that two high-magnitude floods occurring in quick succession, with little time for the basin to recover from the first event, will have greater geomorphological effects than the same floods widely separated in time." For example, the Partnach River (Germany) experienced 2 consecutive, low frequency, high magnitude flood events within a few weeks in 2005. The first flood filled the downstream reaches with sediment. This meant that the river was already in a state of disturbance when the second flood occurred. The downstream channel system was therefore transformed during the second flood (Morche and others, 2007). Wooler Water (Northumberland, UK) was impacted by a 1% annual exceedance probability flood in 2008 followed by a second large flood in 2009 with a similar peak water level, but shorter duration. The 2008 flood generated channel enlargement (deepening and widening) and created additional sediment sources and channel deposits. The 2009 flood caused further bank erosion and reworking/accumulation of channel deposits (Jacobs, 2011).

Catchments experience periods of frequent and infrequent flooding. These periods can last for a season or for decades, during which time the frequency of channel-reforming events varies. In the UK, larger floods often occur in the winter due to increased precipitation and surface run-off as a result of ground saturation (Marsh and others, 2016). In the longer term, Pattison and Lane (2012) found relationships between the systematic organisation of the North Atlantic climate system, which controls weather types in the UK, and periods of elevated and reduced flood risk on the River Eden. Two periods were associated with flood-generating weather types and both of these periods correlated with flood-rich periods, matching with a strong positive North Atlantic Oscillation Index.

When large flood events alter the transport capacity of the channel and river flood plain dynamics, the response of the channel to future flood events may change, as the 'expected capacity for adjustment' in the river evolution diagram contracts or expands (Fryirs, 2017). Naylor and others (2017) describe this process as a feedback mechanism, where extreme floods alter the morphology of a river, which dictates its future response to flood events. Fluvial systems naturally adjust their morphology in response to flood events, which can maintain the ecosystem services provided by a river, for example providing habitat that underpins a productive fishery. Morphological adjustments may increase or reduce flood frequency and extent in response to future high flow events. These are natural adjustments, but if a river erodes its banks to shift the channel closer to properties, infrastructure or agricultural land, or conveyance in a river is reduced in these locations, then the hazard posed by flooding and/or erosion is increased.

Guan and others (2016) investigated the change in channel morphology over a series of hypothetical extreme floods based on a jökulhlaup (glacial outburst flood), which occurred at Sólheimajökull in southern Iceland in 1999. Channel adjustments were shown to mainly occur during the first flood, with 56% erosion and 91% deposition taking place. Morphological adjustment therefore decreased significantly throughout the series of hypothetical floods. Channel conveyance was improved through the upstream reach, as bed scour and incision in some places disconnected the channel from its flood plain and sediment was redistributed to better propagate floodwater. This evidence indicates that extreme floods can efficiently cause a channel to morphologically adjust to convey future high flows. However, in such a scenario, flood hazard may be heightened downstream as floodwater is quickly propagated through the upstream reaches.

During extreme floods, large volumes of sediment are often transported and deposited downstream in lower energy reaches. This reduces downstream channel capacity, therefore, future flood frequency and extent is heightened and the sensitivity to further morphological change is increased (for example, Morche and others, 2007). The upper reach of the River Wharfe (UK) has historically experienced rapid erosion followed by slow aggradation. Through hydrodynamic modelling of the response of future flood extent to short-term morphological change and long-term climatic changes, Lane and others (2007) found that the aggradation of sediment in a channel can significantly increase the magnitude and frequency of inundation events with the same given flow. In their study, 16 months of in-channel sedimentation in an upland gravel-bed river was shown to cause a 50% increase in inundated area, an impact estimated as that arising from more than 30 years of climate change. However, flood response will differ throughout the network and is variable dependent on the size of the flood event (Sholtes and others, 2018), as discussed in the descriptions of process domains in section 2.2.3.

Sediment supply and connectivity

In fluvial systems, sediment transport can be a major factor that determines channel form and morphological response to changes in flow rate (Carson, 1984). This is especially the case for alluvial gravel and cobble-bed rivers that are typical of upland areas in the UK. Sediment supply can vary throughout the catchment and is highly dependent on lateral and longitudinal connectivity. Wohl and others (2016) define connectivity “in terms of the fluxes of material between spatially discrete portions of a landscape, such as hillslopes and channels, or river segments differentiated from one another by longitudinal differences in geometry.” Connectivity can be used to describe fluxes of water, sediment, nutrients and organisms. In this section, we refer to connectivity in terms of sediment flux, but other fluxes are highly linked, so the concept of landscape connectivity should be considered throughout as a key element controlling channel response to flood events. Bracken and others (2015) state that sediment connectivity should be “considered within a nested hierarchy (Harvey, 2002), from local (within landforms), through zonal (sediment transfer between landforms such as hillslope-channel connections), to the behaviour of the whole catchment with linkages along the sediment cascade.”

Mobilisation of sediment in a channel following an input event depends on the magnitude, duration and sequence of flows that exceed the threshold for sediment entrainment, and the characteristics and availability of the sediment. Similar flood events may result in channels exhibiting different morphologies as a result of variations in external sediment supply. A low sediment supply usually results in a well-structured, stable coarse-textured bed that reduces transport rates, while a higher supply results in finer bed sediments, unsorted and unstable bed structures and higher sediment transport rates during a similar flood event (Hassan and others, 2008). Bed structure can also be a reflection of the relative dominance of sediment storage or sediment transfer due to factors such as gradient or lateral confinement. As a result bed morphology may not be solely determined by upstream sediment supply.

Bedload transport and mobility are not easy to monitor during flood events, but general concepts can be extracted from relevant literature. In upland areas, sediment is generally supplied laterally to the system from adjacent hillslopes and debris flows in the headwater reaches. Lateral sediment inputs to the channel depend on hillslope stability, storm frequency and hillslope coupling with the channel. Understanding the type of margin that is confining a channel can provide information about lateral sediment inputs and the extent of coupling to the valley floor (Fryirs, 2013). As shown in Figure 2.8, headwater reaches are confined and therefore well coupled to adjacent hillslopes. The material supplied from the slopes to the headwaters is generally large and therefore can only be moved during infrequent, higher flow events which generate sufficient stream power to transport such material (see section 2.2.1). Flood flows have the potential to entrain large volumes of sediment, which is usually coarser than sediment transported by low flows. For example, a major flood at Raise Beck in 1995 transported boulders with b-axes measuring up to 1,400 mm (Johnson and Warburton, 2002). However, the distances travelled by such large material are usually short.

The mid-reaches are partly coupled, therefore, some sediment is supplied from upstream reaches, tributaries, and reworked materials from bank and bed erosion. Sediment supply is therefore indirectly dominated by hillslope supply, but also partly dependent on the erodibility of the channel margins. Transport of finer material in suspension will occur during low to medium flow events, but coarser grains such as gravels generally require 50 to 60% of bankfull flow to mobilise and move as bedload. The largest bed sediment is only entrained in significant amounts and over longer distances during overbank flows (Joyce and others, 2018). Sediment recruitment in the decoupled, lower reaches is primarily derived from bank and bed erosion, with transfer from upstream providing a secondary source, reflected by the domination of fine sediment in the graph in Figure 2.8. Supply therefore largely depends on the erodibility of the bed and banks (cohesion, vegetation and the actions of aquatic animals have a large influence on this). Once entrained, sediments in these reaches are easily transported in suspension, even during lower flow events, although sediment transport does peak during rarer, higher magnitude flow events (Figure 2.8).

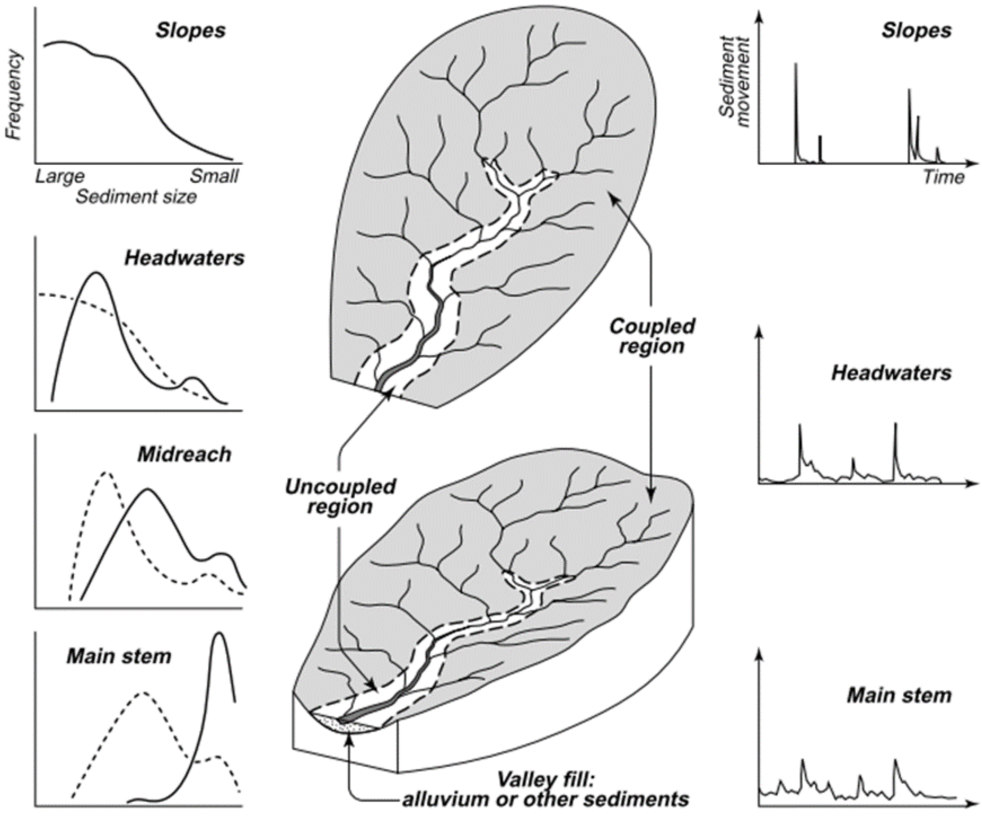


Figure 2-8 Coupling between a stream channel and adjacent hillslopes. Left side: graphs of grain size distribution through the catchment. Right side: graphs to show attenuation of sediment through the catchment, from Church (2002)

The sediment supply may also vary within a reach during flood events, causing higher rates of morphological change in some areas. For example, Dean and Schmidt (2013) found that major geomorphic change occurred around tributary confluences, including channel widening, migration, bar construction and channel braiding. The authors suggest this was due to sudden increases in longitudinal sediment supply at tributary confluences. Rice and others (2000) developed a model to demonstrate the impacts of tributary confluences on abiotic and biotic gradients in river systems. At tributary confluences, abrupt changes were shown to occur in water volume, increased sediment recruitment and bed sediment character, which had an important control on the longitudinal organisation of macroinvertebrate benthos moderate spatial scales. Heritage and others (2004) also observed that geomorphic change at the scale of the channel type on the Sabie River (South Africa) was controlled by flow energy changes, affecting sediment transport (spatial and temporal) and tributary location.

The rate of sediment supply and resulting channel response to flood events also depends on the activity of sediment sources. In the upland, partly confined areas in the Howgill Fells, Harvey (1991) identified 2 types of alluvial channel. Single thread channels exist where there is a fluvial regime with little sediment input due to the inactive gullies on the adjacent hillslopes. Unstable, braided channels occur where active gullies and scars provide a high sediment supply, via cyclic coupling between the gullies and river channel. For example, at Grains Gill, sediment builds up in debris cones below gullies, which is entrained by floods with a 20 to 50% annual exceedance probability. If the debris cones were not removed, vegetation would establish and stabilise them, preventing entrainment during flood events. A flood with a 1% annual exceedance probability occurred in 1982. This resulted in hillslope failure in many locations, causing many previously stable single thread channels to change to braided channels. Since 1982, the destabilised slopes have generally restabilised and become revegetated, causing single thread sinuous channels to take the place of many braided forms (Harvey, 2001). Evidently, when sediment supply to a river exceeds the transport capacity, the river may become extremely dynamic and entire reaches may be transformed (Dean and Schmidt, 2013; Morche and others, 2007). The Howgill Fells example represents the important relationships between water and sediment, which drive channel morphological response during flood events. Similarly, Warburton and others (2002) found that flooding only caused a long-term change in the channel planform of Swinhope Burn, Northumberland if coupled with the influx of coarse sediments from mining waste heaps. Flooding caused a change in morphology from meandering to multi-threaded as coarse sediment blocked the channel, causing channel avulsion. This form persisted while the sediment supply was maintained by mining waste, but when the mine closed the channel reverted back to a single-thread channel.

Fryirs (2017) presents a conceptual model at the catchment scale to represent how the spatial arrangement of blockages such as sediment slugs and dams in relation to the type of flood event can determine the amount of ‘effective’ catchment in operation (that is the ‘connected’ catchment that can contribute sediment to the ‘catchment conveyor belt’ (Figure 2.9). In Figure 2.9a, blockages throughout the catchment reduce catchment connectivity and the majority of the sediment cascade is inactive (switches off). This causes the ‘effective catchment area’ to be low. This is likely to represent a system experiencing high frequency, low magnitude flood events, which limit slope erosion and subsequent fluvial reworking. In Figure 2.9 (b), the catchment is highly connected with an active sediment cascade and large effective catchment area. This situation is likely to occur during a low frequency, high magnitude event, where existing blockages are breached and reworked.

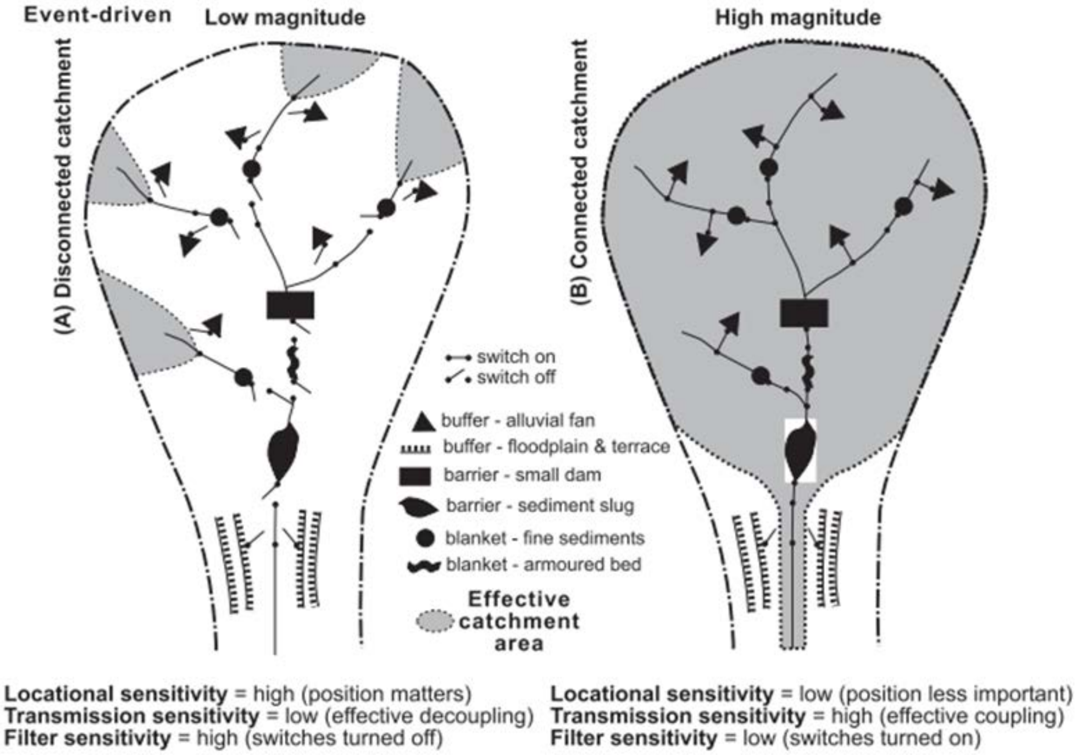


Figure 2-9 Catchment scale (dis)connectivity showing (a) a disconnected and (b) a connected catchment, from Fryirs (2017)

Biological interactions

In the stream evolution triangle, Castro and Thorne (2019) add biology as a primary, high level driver of stream form and evolution, alongside geology and hydrology, stating that “recognition of biology as a driver leads to improved understanding of reach-scale morphology and the dynamic response mechanisms responsible for stream evolution and adjustment following natural or anthropogenic disturbance.” Biogeomorphological research has long investigated the multiway interlinkages between biota and stream morphology, which are key to understanding stream response to flood events (Viles and others, 2008). Biology can have a stabilising effect by causing the system to resist erosion and increase deposition via bioprotection, or a destabilising effect by enhancing erosion and other processes (Table 2.1).

Table 2.1 Ecological impacts on geomorphological systems, from Viles and others (2008)

Stabilising	**Destabilising**
Vegetation growth reduces erosion	Animal burrowing enhances erosion
Microphytic crusts reduce erosion	Animal disturbance to microphytic crusts enhances erosion
Vegetation growth enhances sediment storage	Beaver dams disrupt fluvial systems
Large woody debris in fluvial systems decreases flooding and enhances sedimentation	Large woody debris in fluvial systems increases flooding
Animal grazing enhances vegetation cover and therefore reduces erosion	Animal grazing reduces vegetation cover and therefore enhances erosion

Vegetation is a stabilising factor on hillslopes, as discussed in the above section on sediment supply and coupling. This means that disturbances large enough to affect vegetation cover on hillslopes, such as the 1982 flood event in the Howgill Fells (Harvey 1991, 2011), can have subsequent impacts on run-off and erosion, indirectly impacting downstream hydromorphological response to the event. In the case of the Howgill Fells, major sediment production events contribute to the accumulation of debris cones at the base of gullies. If debris cones are regularly removed by high frequency, low magnitude flood events, the sediment supply is maintained to the system, causing the downstream formation of braided channels. However, if debris cones are not removed, the gully systems would be colonised by vegetation. Dense root networks stabilise gully systems and further reduce sediment delivery to the fluvial system (Harvey, 1988). In the latter areas, fluvial channels are likely to be single thread rather than braided, demonstrating the lack of sediment supplied to the system. However, during high magnitude, low frequency events, such as the 1982 flood, many of these vegetated systems were reactivated, providing significant loads of sediment to the system, causing shifts in channel type (Harvey 1991, 2011).

Vegetation in the riparian and flood plain zones can also have a stabilising effect on geomorphic processes. Riparian vegetation has the most significant influence in lower gradient, laterally unconfined reaches, where vegetation increases the cohesion of riverbanks (Buffington and Montgomery, 1993), making them less sensitive to morphological change during flood events. Riparian vegetation can trap floating material such as sediment, and dense root networks (especially from trees) can increase the erosional resistance of the channel banks. During large flood events, overbank flows may be attenuated by riparian woodland, causing the deposition of transported sediment on the flood plain. This reduces the likelihood of changes to the channel network (for example, channel avulsion) in response to elevated levels of erosion or deposition within the channel (Stoffel and Wilford, 2012).

A study by Gran and Paola (2001) used alfalfa plants to demonstrate that braided river morphology can significantly change in response to increased spatial density of riparian vegetation. Vegetation reduced the number of active channels and increased bank stability, reducing lateral migration, causing narrow and deep channels. Where vegetation was most dense, width to depth ratios were close to those of single thread channels and braiding was reduced, shifting the channel type towards a single thread, meandering river type. Therefore, regular flooding maintains the typical morphology of braided streams, while a period of low flood frequency could cause a shift in river type to a more stable, anastomosed or single thread form, stabilised by riparian vegetation. In contrast, if vegetation is removed from the banks of unconfined, alluvial channels with noncohesive bank materials, major channel response such as widening and braiding could occur during a relatively low magnitude flood (Montgomery and Buffington, 1993).

Riparian vegetation can also contribute large wood to the fluvial system. Large wood can have stabilising and destabilising impacts on channel morphology (Table 2.1), by causing (1) flow deflection and local scour pools to develop where flow converges, (2) deposition where flow diverges and (3) sediment impoundment (Buffington and Montgomery 1993). While large wood drives both local scour and deposition, field observations by Wallerstein and Thorne (2004) indicated that the net effect of large wood was to reduce the time needed for unstable, incised streams in North Mississippi to recover their stability. Marcus and others (2002) demonstrated that the effect of large wood on channel morphology depends on channel size. In smaller channels, large wood remains in situ except for during higher magnitude flow events as it is generally too large to be mobilised, while in larger channels large wood is regularly reorganised by in-bank flows. Therefore, the most stable morphologies resulting from large wood may be found in smaller channels, often in the upper reaches of a catchment (Figure 2.10). In these smaller channels, large wood may be the dominant control in forcing morphological features such as pools and bars, where the dominant morphology would otherwise be a uniform plane-bed (Montgomery and Buffington 1993). In Figure 2.11, Wohl and others (2019) illustrate how the wood regime varies spatially throughout the catchment such that a range of morphologies may result, with increasing sensitivity, downstream.

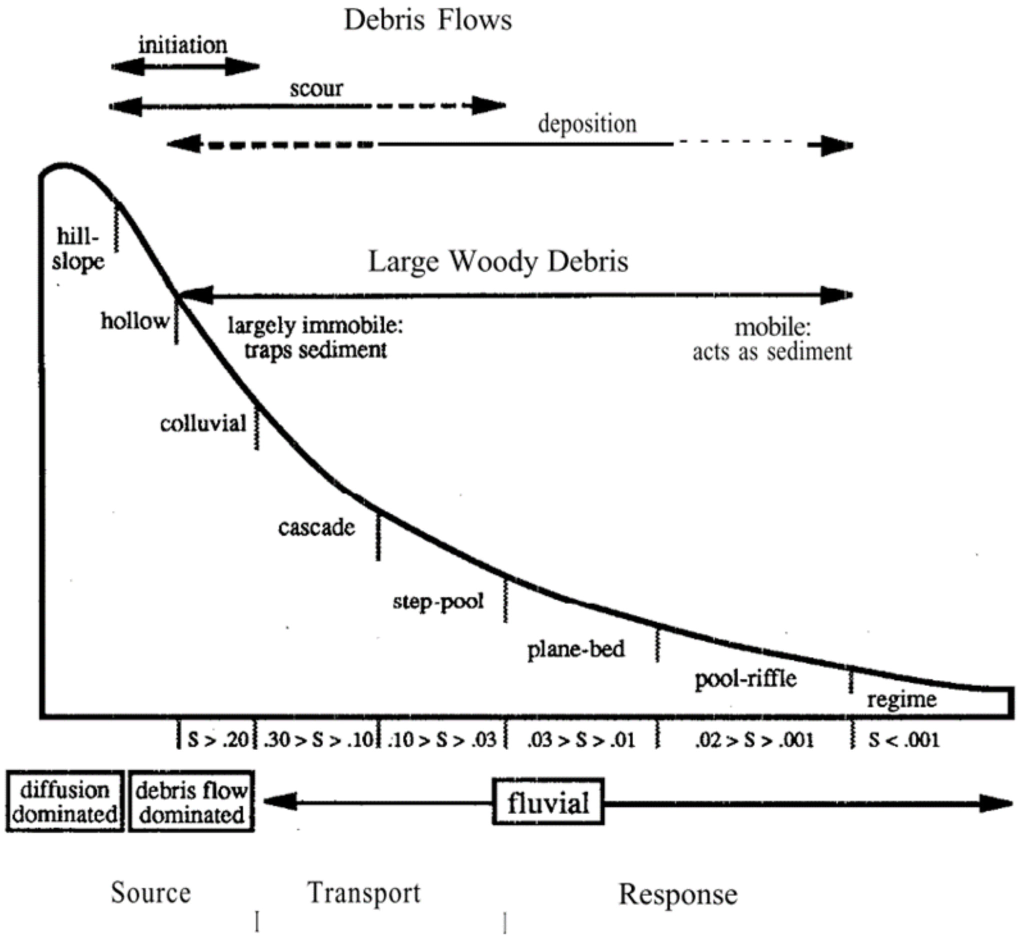


Figure 2-10 Conceptual long profile of a river through the catchment, showing the influence of large wood at different locations in the network, from Montgomery and Buffington (1993)

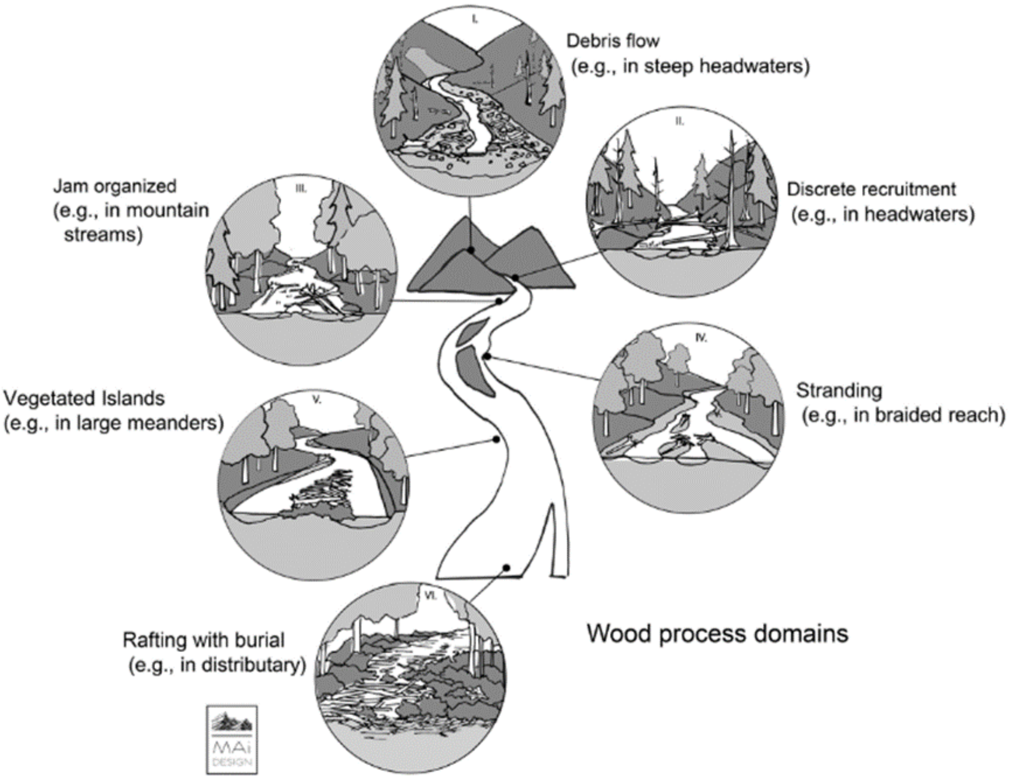


Figure 2-11 Hypothetical wood process domains along a river continuum, from Wohl and others (2019)

Large flow events have the capacity to (re)distribute large wood throughout the catchment. Log jams may already exist within the catchment and be redistributed, even if they have been stationary for a long period of time in smaller upstream channels (Morche and others, 2007; Wondzell and others, 1999). In addition, high velocity overland flows may strip vegetation from the flood plain and deliver it to the channel (Magilligan and others, 2015; Baker and others, 1977), or riparian trees may be recruited as channel banks erode. In the Partnach River, a large flood wave removed 151 large wood dams in 2005. However, after the event, 154 dams were mapped, which were most likely a result of tree recruitment associated with bank erosion. Approximately 71 tonnes of alluvial sediment had aggraded upstream of these large wood dams, which is roughly five times the mean annual bed load export of the Partnach River (Morche and others, 2007).

In the Lookout Creek catchment (US), a large amount of large wood was in the channel during a flood event in 1996. A number of large wood dams were breached, which caused scour of aggraded upstream sediment and bed degradation in localised reaches. Large wood was deposited on the river banks, which acted to confine the channel and exacerbate bed degradation. Large wood also blocked active channels in some reaches, where the channels lacked the transport capacity to carry logs further downstream. This caused sudden lateral adjustments in channel alignment (Wondzell and others, 1999). In contrast, large wood may have a stabilising effect during larger floods. For example, Surian and others (2016) found that large riparian trees adjacent to large wood dams had a protective role in reinforcing the banks, which may have reduced localised channel widening. It was also suggested that large wood may have reduced the sediment supply from landslide material in some locations.

Therefore, large wood that enters the channel during a flood event can accentuate the morphological response of a channel in ways that can persist over a range of timescales, dependent on channel size, gradient and location in the catchment. In smaller channels, morphological responses to the input of large wood may persist over decades, while impacts on the flood plain may persist over centuries (Figure 2.12; Viles and others, 2008). In addition, trees transported downstream in flood events can block bridges and structures, which can have proportionately greater morphological impacts. Significant transport of large wood in the Magra River during the 2011 flood is likely to have intensified both morphological and economic/societal impacts where bridges were blocked by transported wood. During the Lynmouth Floods of 1952, log jams were highlighted as the cause of the flood waves. Many bridges were inadequate to withhold the volume of water, trees and boulders that built up behind them, causing damage to a number of structures and flood waves downstream (Green, 1955). For this reason, large wood is often removed by default in many rivers in the UK, although there is a growing recognition that this removal process needs to be much more restricted to high risk areas, due to the negative geomorphological and ecological repercussions that follow wood being removed.

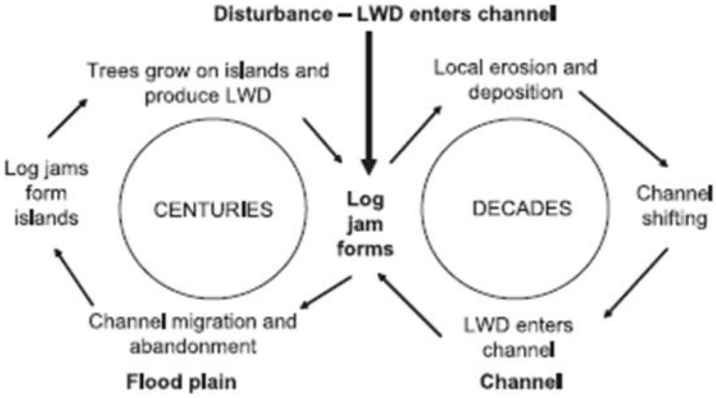


Figure 2-12 Morphological impacts of large wood input, over decades and centuries, from Viles and others (2008)

Animals can also alter the morphological response of a river to flood events, either by stabilising or destabilising a fluvial system. Macroinvertebrates have been shown to significantly reduce bed mobility. For example, studies on the River Soar (Leicestershire, UK) by Johnson and others (2009) revealed that fine gravels colonised by caddisfly (*Hydropsychidae)* needed significantly greater shear stresses to entrain them than uncolonised gravels. In contrast, signal crayfish (*Pacifastacus leniusculus)* have been found to increase the amount of sediment entrained under higher velocity flows, as they disturb gravel by making pits and mounds. Therefore, this invasive species could enhance coarse-grained bedload flux in a number of UK rivers during high velocity events, therefore altering the morphological response (Johnson and others, 2011). The impact of beavers on fluvial geomorphology and flood response has been well documented in the USA (for example, Gurnell, 1998) and is particularly relevant in the UK as more beavers are being reintroduced in various catchments, such as the River Otter and River Tay. Beavers require approximately 70 cm deep, slow-flowing water to increase the security of their lodges. In sub-optimal conditions, where deep water does not exist, beavers construct dams and dig canals, significantly increasing the morphological complexity of the landscape (Elliott and others, 2017). Dams cause upstream impoundment of water and sediment trapping in ponds. In the River Otter, a series of beaver dams in headwater streams has been shown to attenuate flows due to the storage of water in upstream beaver ponds and increased hydraulic roughness of the channel. As leaky dams continuously drain, regaining storage capacity in the beaver ponds, flood peaks are reduced, even in saturated conditions (Puttock and others, 2017). This attenuation reduces morphological impacts of the flood downstream. However, at the location of the dam, the build-up of water and sediment trapping upstream during flood events may cause channel avulsion, where a new bypass channel is formed to the side of the dam.

2.2.3 Channel stability by process domain

Floods of different magnitude, frequency and duration may cause a range of morphological responses, determined by the existing morphology of the channel and previous controls. Channels can be classified into different types, reflecting the balance of driving and resisting forces (water, sediment and biotic interactions) outlined in the above sections. According to Montgomery and Buffington (1993), "the morphology and sediment transport dynamics of a channel reflect the style, magnitude and frequency of both sediment and water input from upslope sources, the ability of the channel to transmit these loads to downslope reaches and the influence of vegetation on channel processes."

Channel type dictates the response of a river to a flood event. For example, a flood of moderate magnitude in a bedrock channel may not have a significant impact on morphology, while the same magnitude of flood may cause significant changes to a sinuous alluvial channel, such as channel widening, incision or increased sinuosity (Death and others, 2015). On the other hand, a large magnitude flood in the lower reaches of a river may be attenuated by flowing over the flood plain, while a flood of the same magnitude would be confined within a narrow bedrock channel upstream. The degree of change often depends on the channel form and how close it lies to a geomorphic threshold, that is, how close the channel is to becoming an alternative form.

To summarise information from the previous sections, we outline 4 broad process domains in a fluvial system, from source to mouth, in which the response of the system is relatively similar. The typical morphological responses of specific channel types within these domains and their overall general morphological stability are detailed below and in Figure 2.13 and Table 2.2. We use Church's (2002, 2006) classification of 6 alluvial channel types based on bed mobility, which is measured by the bankfull Shields stress (the relative mobility of the median grain size at bankfull). This classification therefore provides a good indication of morphological stability of a channel in relation to flood flows.

A number of case studies are also provided to demonstrate typical behaviour of a channel type in response to flood events. We accept that there are exceptions to this conceptual model (some of which are discussed in section 2.2.4), but it does explain a general spatial pattern of morphological response to floods of varying magnitude/frequency throughout the catchment.

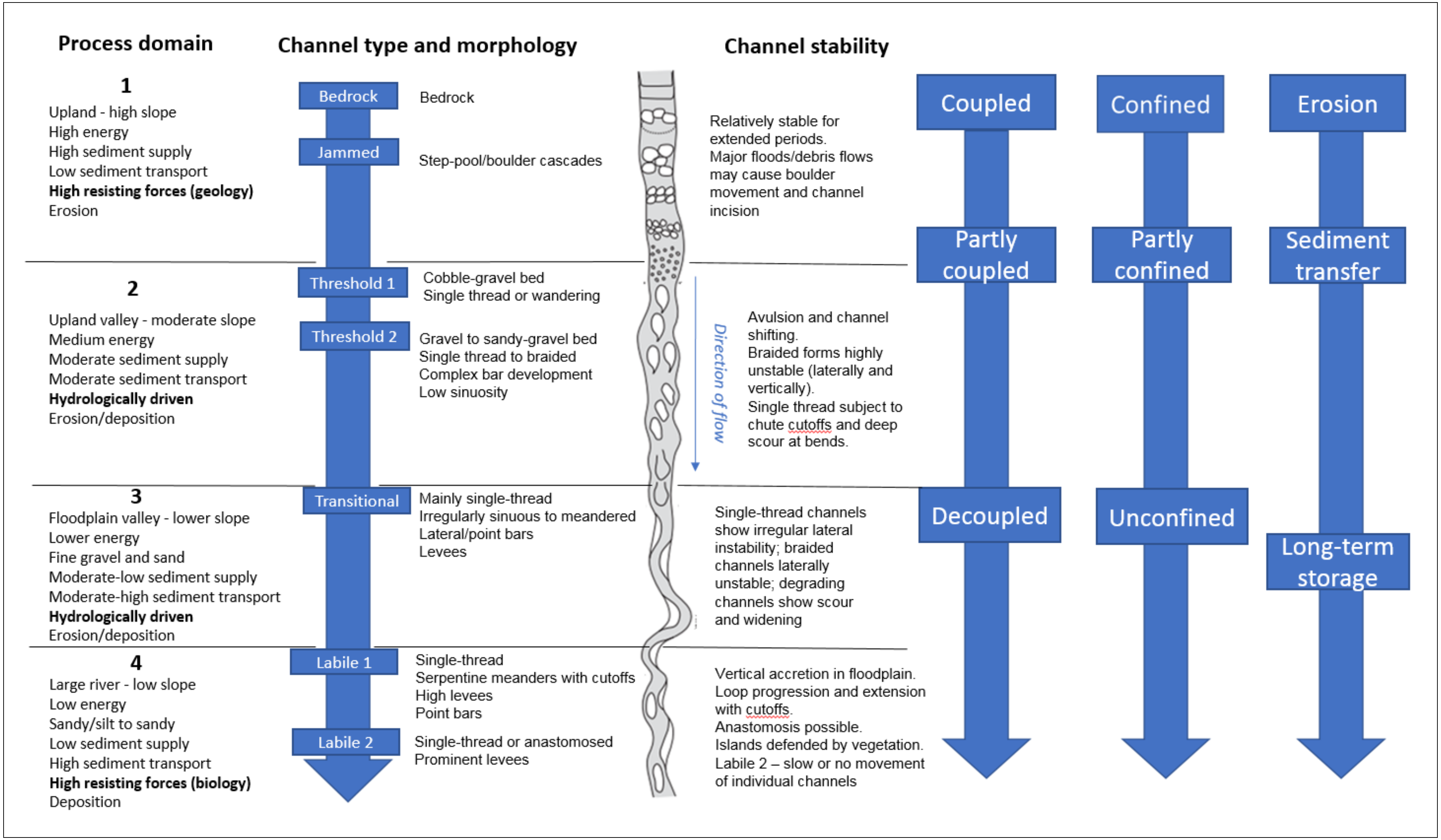


Figure 2-13 Channel classification by process domain and stability, modified from Church (2006) and Fryirs (2017)

Channel type/Bankfull Shields stress (τ_{*bf})[a]	Sediment type	Sediment transport regime[b]	Channel morphology[c]	Channel stability
Jammed channel; $\tau_{*bf} = 0.04^+$	Cobble- or boulder-gravel	Low total transport, but subject to debris flows; bed load transport is a high percentage of the total load (q_b/q_t typically $>10\%$)	Step-pool or boulder cascades; width typically a low multiple of largest boulder size; Slope (S) $>3°$	Stable for long periods of time with throughput of bed load finer than structure-forming clasts; subject to catastrophic destabilization in debris flows
Threshold channel; $\tau_{*bf} = 0.04^+$	Cobble-gravel	Schumm's "bed load" channels; low to moderate total transport, with a high percentage of bed load (q_b/q_t typically $>10\%$), but usually limited to partial mobility (*sensu* Wilcock and McArdell, 1993)	Cobble-gravel channel bed; single thread or wandering; highly structured bed; relatively steep; low sinuosity; width-to-depth (w/h) >20, except in headwater boulder channels	Relatively stable for extended periods, but subject to major floods causing lateral channel instability and avulsion; may exhibit serially reoccupied secondary channels
Threshold channel; τ_{*bf} up to 0.15	Sandy-gravel to cobble-gravel	Moderate total transport, with a moderate to high percentage of bed load (q_b/q_t typically 5–10%); partial transport to full mobility (*sensu* Wilcock and McArdell, 1993)	Gravel to sandy-gravel single thread to braided; limited, local bed structure; complex bar development by lateral accretion; moderately steep; low sinuosity; w/h very high (>40)	Subject to avulsion and frequent channel shifting; braid-form channels may be highly unstable, both laterally and vertically; single-thread channels subject to chute cutoffs at bends; deep scour possible at sharp bends
Transitional channel; $\tau_{*bf} = 0.15–1.0$	Sand to fine gravel	Schumm's "mixed load" channels; moderate to high total transport, with a moderate percentage of bed load (q_b/q_t typically 3–5%); full mobility, with sandy bed forms	Mainly single-thread, irregularly sinuous to meandered; lateral/point bar development by lateral and vertical accretion; levees present; moderate gradient; sinuosity <2; $w/h > 40$	Single-thread channels, irregular lateral instability or progressive meanders; braided channels laterally unstable; degrading channels exhibit both scour & channel widening
Labile channel; $\tau_{*bf} > 1.0$	Sandy channel bed, fine sand to silt banks	Schumm's "suspended load" channels; high total transport, with a low to moderate percentage of bed load (q_b/q_t typically 1–3%); fully mobile, sand bed forms; sediment transport at most stages	Single thread, meandered with point bar development; significant levees; low gradient; sinuosity >1.5; $w/h < 20$; serpentine meanders with cutoffs	Single-thread, highly sinuous channel; loop progression and extension with cutoffs; anastomosis possible, islands are defined by vegetation; vertical accretion in the floodplain; vertical degradation in channel
Labile channel; τ_{*bf} up to 10	Silt to sandy channel bed, silty to clay-silt banks	High total transport, almost exclusively suspended and wash load (q_b/q_t typically $<1\%$); minor bed form development	Single-thread or anastomosed channels; prominent levees; very low gradient; sinuosity >1.5; $w/h < 15$ in individual channels	Single-thread or anastomosed channels; common in deltas and inland basins; extensive wetlands and floodplain lakes; vertical accretion in floodplain; slow or no lateral movement of individual channels

[a] The bankfull Shields stress describes the relative mobility of the median grain size (D_{50}) at bankfull flow. $\tau_{*bf} = \tau_{bf}/[(\rho_s - \rho)g\,D_{50}]$, where τ_{bf} is the bankfull shear stress, ρ_s and ρ are the sediment and fluid densities, respectively, and g is the gravitational acceleration. Where bankfull information was unavailable, other channel-forming flows were used by Church (2006) (e.g., the 2-year or the mean annual flood).

[b] Descriptions modified from those given by Church (2006). Bed load percentages are estimated and can vary considerably with basin geology (e.g., lithologies that naturally produce high sand/silt loads), geomorphic history (e.g., occurrence of loess deposits, fine-grained glacial outwash, or volcanic ash) and land use (e.g., roads, mining, and agriculture).

[c] Channel morphologies shown in Figure 5.

Source: Modified from Church, M., 2006. Bed material transport and the morphology of alluvial rivers. Annual Review of Earth and Planetary Sciences 34, 325–354, with permission from Annual Reviews, Inc.; based on concepts from Schumm (1963a, 1971, 1977, 1985) and Dade and Friend (1998).

Table 2.2 Classification of channels and riverine landscales, from Buffington and Montgomery (2013), modified from Church (2006)

Process domain 1

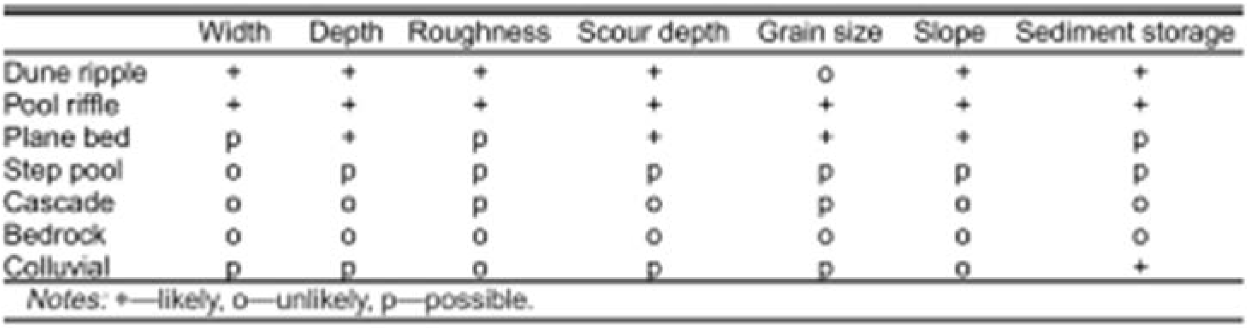
Process domain 1 is characterised as an upland, high gradient and confined environment, creating high energy conditions. Channels in this process domain could be grouped towards the ‘geology’ corner of the stream evolution triangle (Castro and

Thorne, 2019). These reaches are typically referred to as the ‘source’ reaches, where the channel is well coupled with the hillslopes, therefore, the channel receives large loads of sediment. However, low transport capacities in relation to the size of the material mean that large boulder clasts are relatively immobile in the channel during bankfull conditions, as reflected by the low Shields stress values for jammed and threshold channels in Table 2.2. Three types of channel can be grouped within process domain 1: bedrock (non-alluvial), jammed and threshold 1 (alluvial). Threshold 1 channel types are in the transition between process domain 1 and 2.

The geometry of bedrock channels does not generally change in response to flood flows. High levels of confinement create resisting forces (geology) that are typically higher than driving forces (stream power), which make the channels insensitive to change during low-moderate flood events. These reaches are effectively the source of sediment and water to the fluvial system, transmitting sediment and water to downslope reaches without significantly modifying the reach (Montgomery and Buffington, 1993).

Jammed channels are the steepest alluvial channels in the classification. These channels are also unlikely to change significantly, except during major flood events. They are characterised by step-pools and boulder cascade morphologies. Although these channels can be stable for long periods of time, extreme floods may entrain large boulders and large wood. The average particles of these morphologies are large in size relative to flow depth, which cause them to be immobile in low to moderate flow conditions. However, some gravels are present, generally in low energy conditions upstream of flow barriers such as relatively immobile large wood and larger clasts. This is especially the case in step-pool morphologies, where larger clasts are organised into a series of steps, with pools in between containing finer material. Warburton (2002) suggests 3 phases of sediment transport in step-pool morphologies, where fines are readily entrained from pools during low flows, gravel and underlying fines are mobilised during frequently occurring higher flows, while large step boulders are transported during low frequency high magnitude events. For example, a major flood at Raise Beck (a steep mountain torrent) in 1995 transported boulders with b-axes measuring up to 1,400 mm (Johnson and Warburton, 2002).

Generally, the morphologies of bedrock and jammed channels are resilient to moderate changes in sediment supply and discharge, as presented in Table 2.3.



	Width	Depth	Roughness	Scour depth	Grain size	Slope	Sediment storage
Dune ripple	+	+	+	+	o	+	+
Pool riffle	+	+	+	+	+	+	+
Plane bed	p	+	p	+	+	+	p
Step pool	o	p	p	p	p	p	p
Cascade	o	o	p	o	p	o	o
Bedrock	o	o	o	o	o	o	o
Colluvial	p	p	o	p	p	o	+

Notes: +—likely, o—unlikely, p—possible.

Table 2.3 Channel morphology response potential to moderate changes in sediment supply and discharge, from Montgomery and Buffington (1997)

Process domain 2

Process domain 2 is characterised as an upland valley, moderate to steep gradient and partially confined environment (Figure 2.13). Channels in this process domain could be grouped mainly towards the ‘hydrology’ corner of the stream evolution triangle (Castro and Thorne 2019). These reaches are still fairly well coupled with hillslopes and transport significant amounts of material downstream. Two types of alluvial threshold channel can be grouped within process domain 2, which are broadly similar in that they are bed load dominated, but have slightly different thresholds of sediment mobility.

By comparing historical maps Hooke and Redmond (1989) identified that most adjustments of the lateral planform are concentrated in the margins of the uplands, for example the piedmont areas (the margins of upland areas), but channel sensitivity varies from river to river and reach to reach. These rivers are downstream of the upland bedrock reaches and flow through coarse erodible alluvial deposits. Stream gradients here are relatively steep, creating high stream power, erosive conditions during higher magnitude flood events.

The morphology and response of channels in this process domain greatly depends on patterns of confinement and sediment supply, as the channel moves between the confinement of somewhat erodible valley bottom margins and less confined areas, where pockets of flood plain may exist. Dean and Schmidt (2013) suggest that confined channels may be relatively unresponsive to large flood events, but can cause major geomorphic change in reaches upstream and downstream. During a flood event in 2008 in the Rio Grande (USA), water was observed to pool upstream of confined areas, with the confined section acting as a ‘hydraulic jet’ and vast sediment deposition occurring downstream of the constriction where velocities suddenly decreased. The flood plains of St John’s Beck, Cumbria, UK were found to be a major sink for coarse sediment following Storm Desmond in 2015, but only where the channel was unconfined. During this event, 6500 ± 710 t of sediment was eroded from the river flood plains, banks and bed and 6300 ± 570 t of sediment was deposited in the channel or on the surrounding flood plains. Very coarse clasts were deposited across flood plains and terraces, which interrupted the normal fining sequence of the deposits. Large, imbricated clasts were found in the riparian zone, sometimes up to 4 m above the channel bed. Only <6% of mobilised sediment was transported downstream of the 8 km channel, indicating that the upper flood plain can act as a significant storage zone during major floods, which has the potential to disrupt sediment continuity downstream (Joyce and others, 2018).

Threshold 1 channels may contain some step-pool morphologies, as in some channels in process domain 1. However, channels are generally single-thread or wandering. Sediments are mainly dominated by cobbles and gravels and are bed load transported. However, the large size of the clasts reduce the capacity of the stream to transport sediment during low-moderate flood events. Channels such as this may remain stable for long lengths of time during recurrent flood events, but extreme floods can cause lateral instability and avulsion, where channels reoccupy former channels (Church, 2006). A major flood event on the mountain torrent Raise Beck in the Lake District caused a large channel avulsion at the fan apex, which resulted in the A591 trunk road being blocked and caused local flooding (Johnson and Warburton, 2002). Milan (2012) found that typical bankfull flows on Thinhope Burn would not have the capacity to mobilise stored alluvium on the valley floor, limiting the geomorphic response of the river. However, during large events, more of the valley floor is inundated, which increases valley floor working and transport of coarse material.

Threshold 2 channels contain slightly finer material, such as sands, alongside gravels and cobbles, which increases the mobility of sediments during bankfull events. These channels can be single-thread or braided, highly dependent on the sediment supply to the channel and the level of confinement in the reach. As described in section 2.2.2, in the Howgill Fells, an extreme flood in the 1980s was observed to shift the channel morphology from single-thread to braided, as the heavy rainfall triggered neighbouring landslides and the flood coupled the hillslopes and fluvial system (Harvey, 1991, 2001, 2002). A braided channel is likely to become more braided during extreme flood events, with associated lateral shifting (Hooke and Redmond 1989). Indeed, the large area required for the lateral morphological adjustment of 5 alpine gravel bed rivers in Austria as a consequence of extreme floods (recurrence interval more than 100 years) put adjacent buildings and infrastructure at risk (Krapesch and others, 2011).

During flows exceeding bankfull, single thread channels may exhibit chute cutoffs, where the river cuts across meander bends as deposited sediment locally increases the gradient over a point bar and the cutoff is the most direct route for excess floodwater across the flood plain. This process can greatly reduce sinuosity, as occurred on Raise Beck in response to a large flood in 1995 (Johnson and Warburton, 2002). A number of cutoffs occurred on one reach of the River Bollin during the large floods of winter 2000 to 2001. Hooke (2004) suggested that although the floods caused the cutoffs, over the longer term the river had reached a critical threshold at which point a large flood was able to trigger significant change in morphology.

Process domain 3

Process domain 3 is characterised as a flood plain valley, with lower slope gradients and limited geological lateral confinement. These channels still transfer some sediment supplied from upstream, therefore their morphologies are dependent on longitudinal coupling with upstream reaches. Transitional channels are the only channels grouped in process domain 3.

Transitional channels reflect a transition between threshold and labile channels, where the dominant sediment is sand and fine gravel, with a high proportion moving in suspension. Higher peak flows may increase the sediment transported into the reach from upstream, but as sediment moves through these transitional zones some size fractions may be stored and this can lead to the bed sediments coarsening. Transitional channels typically have a single channel and may be meandering or sinuous, with depositional features within both the channel and the flood plain, due to reduced stream powers in response to lower stream gradient and the lateral unconfinement of the channel. Braiding can occur locally where sediment inputs exceed transport capacity.

Montgomery and Buffington (1993) suggest that riffle-pool channels have a wide variety of responses and are likely to respond to moderate flow events (Table 2.3). As they are generally unconfined, widening is a common response to increased discharge, which may also cause bank undercutting and meander development, which could further reduce channel slope. The variation in behaviour shown in transitional channels is usually expressed morphologically. Single thread transitional channels often have a relatively stable morphology with a riffle-pool sequence; but these may also exhibit irregular lateral instability where scour and channel widening takes place due to morphological variation in the existing channel – whether caused by variation to the local gradient, resistance of the channel boundary, sediment input or planform. Sinuosity is of particular importance: many studies have found that geomorphic response to large floods is increased in areas of high sinuosity. Channel widening is often greatest at meander bends during large floods, as flow velocities are concentrated into the outer edge of the meander, causing lateral erosion. Although Tropical Storm Irene had a major geomorphic impact on the Saxtons River Basin in 2011, channel widening was localised to meandering sections and did not occur throughout the catchment as the lower catchment has low sinuosity (Magilligan and others, 2015). Similarly, a study by Buraas and others (2014) found that where unit stream power and bend stress parameter were high, mid-channel islands were infrequent and widening generally occurred due to bank erosion at channel bends. However, where stream power and the bend stress parameter were low, channel widening generally occurred in association with vegetation stripping from the upstream end of mid-channel islands.

During a large flood event with a 30 to 200-year recurrence interval, significant widening occurred along the middle reaches of the Magra River (central-northern Italy) (Nardi and Rinaldi, 2015). Mean widening along the reach was 35 m, which was a mean change of approximately 30%. This was caused by the erosion of lateral riparian areas and in-channel islands, in addition to the deposition of overbank coarse sediment on the adjacent lower flood plain. As flow velocities and resulting erosion rates are higher at the outside bend of meanders, widening may be more severe at channel bends (Magilligan and others, 2015) and some channels may migrate laterally during flood events, especially in unconfined areas (Sholtes and others, 2018).

Similarly, Dean and Schmidt (2013) found that geomorphic change was greatest in areas of high sinuosity in the Johnson Ranch and Boquillas reaches of the Rio Grande (US) during a large flood in 2008. Stream power was increased at meander bends, causing significant channel widening, migration and channel avulsions in these locations. Flood water flowed over the flood plain to occupy the ‘path of least resistance’, which stripped the insides of meander bends of vegetation and fine sediment, leaving exposed basal gravels and cobbles. See process domain 2 for an explanation and examples of chute cutoffs. Figure 2.14 shows a good example of the historical development of the Bloody Inches oxbow in the lower reaches of the River Tay, Scotland (Paine and others, 2002). Two active channels existed between 1783 and 1827, but a cutoff was commenced between 1746 and 1783, most likely in association with major flood events in 1761, 1767 to 1768, 1773 to 1774 and 1780 to 1781. Final isolation of the oxbow from the main channel was a result of flood embankment construction between 1827 and 1864.

Flows that exceed bankfull may leave significant accumulations of sediment on the flood plain. Lambert and Walling (1987) investigated sediment deposition on the flood plain of the lower River Culm, Devon, a fine gravel bed river with a well-developed flood plain. Overbank flooding is frequent during the winter and during major floods can inundate approximately 5.5 km^2 of flood plain between Cullompton and Stoke Canon. Between November 1982 and May 1984, 25 storm events occurred, 15 of which caused substantial overspilling onto the flood plain. During these events, a downstream reduction in suspended sediment concentration was apparent, with conveyance losses of 8 to 54%. Each year, it was found that 28% of the upstream suspended sediment load may be deposited on the flood plain of this reach.

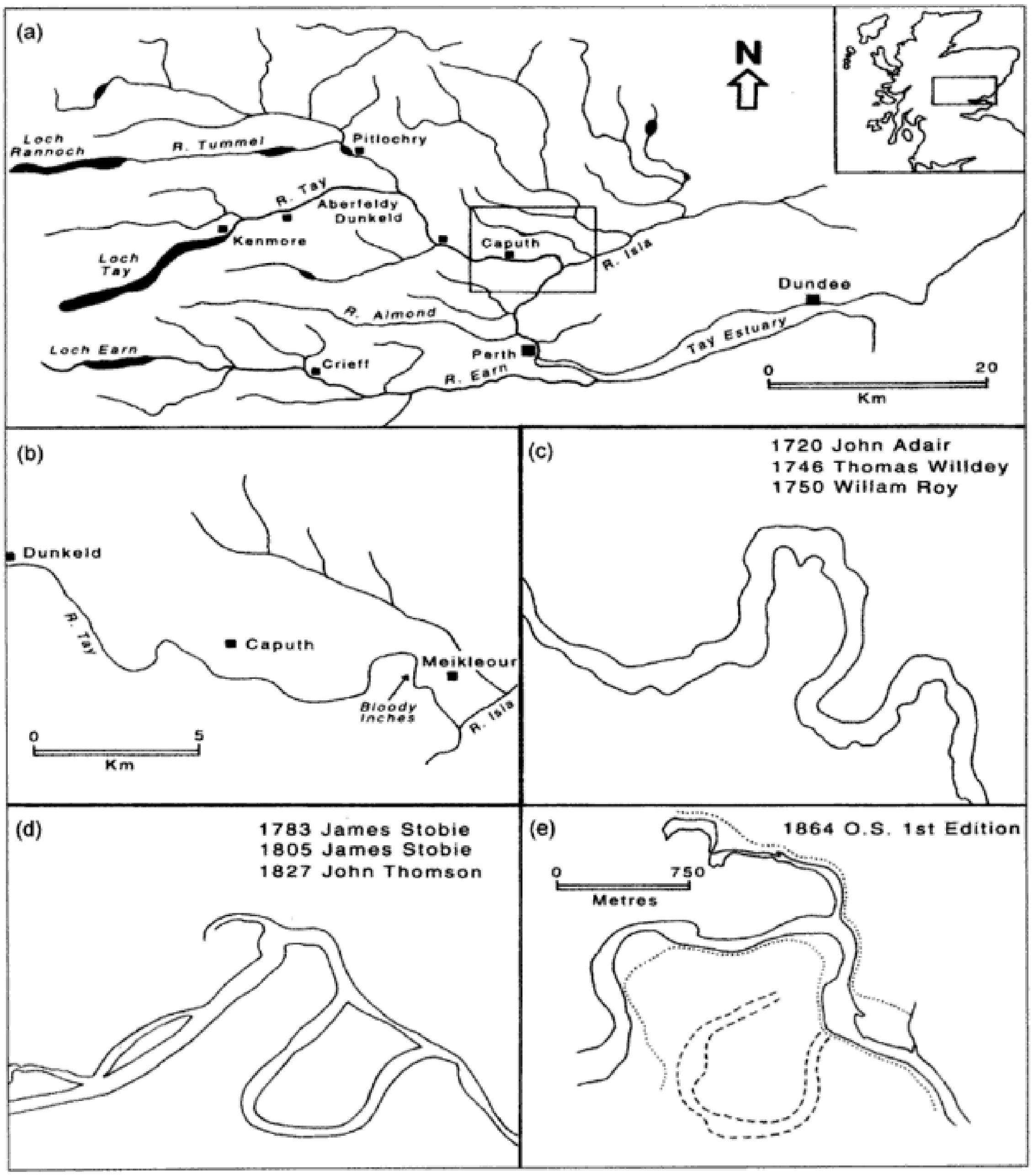


Figure 2-14 (a) Geographical location of the River Tay drainage basin, (b) study area, (c)-(e) historical development of the Bloody Inches oxbow, from Paine and others (2002)

Process domain 4

Process domain 4 rivers are characterised as large, laterally unconfined rivers with low slope gradients, and low energy conditions (Figure 2-13). These channels have high bed mobility, with the majority of sediment (sands, silts) carried in suspension for the most of the time. Two types of labile channel are grouped into process domain 4, where labile 1 is differentiated from labile 2 by the increased mobility of finer bed sediments at bankfull in labile 2 channels. Labile channels are single-thread or anastomosed, with high sinuosity and occasional cutoff formation during high flows (see process domain 2/3).

In this process domain, channel-reforming flows could be said to occur at high annual exceedance probability, as such flows are capable of entraining the fine sediment present in the channel. However, bed instability is inherent to the behaviour of the system and therefore morphological change depends on bank stability and gross sediment exchange (Church, 2002). As channels in this process domain are mostly laterally unconfined, the channel has the potential to adjust its form across the flood plain. However, in a narrow valley a laterally confined channel could shift closer to a confining margin, which could have impacts on future channel response (Fryirs, 2016).

Channels in this process domain are generally laterally stable, as in an unconfined flood plain setting the lateral spreading of overbank flows limits the depth of flow and associated basal shear stress to that caused by bankfull flows, which reduces the impact of peak discharges on channel morphology. For example, during the large flood events of 2012 to 2014, the Thames showed little morphological channel response despite high rates of discharge. The low channel slope and large flood plain width constrained stream powers to lower values than the erodibility of the channel margins (D. Sear, pers. comm.). In addition, the margins of large river systems are often densely vegetated, creating high bank resistance (grouped towards the 'biology' corner of the stream evolution triangle (Castro and Thorne, 2019)). However, removing bank-stabilising vegetation could result in dramatic channel widening and morphological change during flood events.

Deposition via vertical accretion in the flood plain is therefore the primary morphological process during flows that exceed bankfull. In these systems, flood plains can act as important sinks for suspended sediment during larger flood events. Higher sediment delivery from upstream reaches during flood events may cause vertical aggradation of the flood plain. For example, severe flooding in the Severn catchment in January 1998 caused a layer of sediment to accumulate across the flood plain at Tewkesbury, measuring 0.7 cm thick at the riverbank (Zhao and others, 1999). Deposition also occurs within channels, which can cause a system of narrow, deep multi-threaded channels to develop. These anastomosed systems are usually highly stable due to the dense root networks of vegetation on the channel banks and in-channel islands. Smith (1976) found that dense growth of meadow grass and scrub willow offered anastomosed channels in fine sediment flood plain deposits in the Alexandra Valley, Banff Park, Alberta a high level of protection. Results from the study showed that a typical bank of the area, that is bank sediment with 16 to 18% by volume of roots with a 5 cm root mat for bank protection, was 20,000 times more resistant to erosion than comparable unvegetated bank sediment. Therefore, only 4.2 cm of lateral migration was predicted to occur each year.

2.2.4 Human influence on channel response

Human modifications can affect channels in different ways, altering the morphology, discharge and/or sediment load of the river (Hooke and Redmond, 1992). Modifications such as channelisation, bank armouring, dam and weir construction can reduce the morphological response of a reach to a large flood event, but the whole system response can be more complex, with an increased response to high flows downstream or if the modifications fail during the flood. The river evolution diagram (Brierley and Fryirs, 2016) shows how human disturbance can restrict or expand the expected capacity for adjustment of a river, which can trigger irreversible river morphological change in response to disturbance, for example flood events (section 2.1.2). Key natural processes allowing different fluvial systems to adjust morphologically to a wide range of flood flows may be altered by human disturbance, causing rivers to respond in a completely different way to that anticipated for the type of channel in its natural state. Concepts of lateral and longitudinal coupling and connectivity, discussed in the above sections, may be reduced by human modifications to the channel and flood plain, which may cause catchment-wide, as well as reach-scale impacts. A range of human modifications, which can affect the scale and impact of flood flows on river morphology, are discussed below.

Anthropogenic constriction and confinement of flows

Modifications to channel-floodplain connectivity can have significant consequences for the effects of flooding (Montgomery and Buffington, 1993). Infrastructure on flood plains can restrict and confine morphological adjustment of rivers during flood events, concentrating flows through an unusually small flow area. This increases velocity and boundary shear stress and, depending on the boundary strength of the channel, causes channel widening/bank erosion that undermines structures. Sediment deposition may occur downstream of constrictions where flow velocities are reduced. In many cases, artificially confining a channel and disconnecting the channel from its flood plain causes an unconfined lowland river (for example, process domain 3 or 4) to respond to flood flows in a similar way to a highly confined, bedrock reach (for example, process domain 1). Whereas the river would have previously overspilled onto the flood plain during over bank flows, flood flows are now artificially contained within the channel. Therefore, increased stream power in artificially confined reaches may cause bed scour and incision, which further increases the confinement of the channel and the transport capacity of the channel (Joyce and others, 2018; Death and others, 2015). The impacts of channel modification on morphological response to floods may be more visible downstream. Joyce and others (2018) found that although erosion of the channel bed and banks occurred in upstream artificially confined areas, extensive overbank deposition occurred in unconfined downstream reaches, where flow velocities were dissipated over the flood plain.

Channelisation, which was frequently undertaken in the latter half of the 20th Century, typically involves creating a simple, smooth channel with a more uniform width and depth. This was often undertaken with the dual aims of improving land drainage during low flows and reducing overbank flooding by increasing the volume of water that the channel can accommodate during high flows. How channelization is undertaken depends on the existing channel: it may involve narrowing and deepening where the natural channel is relatively wide and shallow; or widening channels and removing bars elsewhere. Channelization often meant deepening the channel to drain the land.

Since water and sediment continue to move downstream through channelized rivers, there is often some form of morphological response to the channelization. The type of response varies depending on the site. In overwide sections the morphological adjustment during flooding may be limited due to low stream power, and as a result narrowing may occur as finer sediments are deposited during lower flows and biotic processes may become dominant.

The deepening that often accompanies channelisation can lead to a steep section of channel bed at the upstream end of the works, increasing the water surface slope and causing bed erosion that can then propagate into upstream reaches during flooding; channel incision and bank undercutting follow, which steepen the banks and make them prone to bank failure, widening the channel. These processes generate sediments that are often deposited in the downstream channelized reaches. If the deposited sediment forms a plug, channel avulsion may occur as the channel attempts to morphologically adjust back to its natural state. Water that spills onto the flood plain may flow in palaeochannels. Downs (1994) investigated river channel adjustments in response to management in the Thames Basin, UK. In channels straightened in this century, deposition was found to be the dominant process in lower gradients (<0.0050), while erosional enlargement generally occurred in higher gradient channels and upstream reaches. Channels channelised before this century were generally found to be morphologically stable.

Morphological adjustment of the modified reach may be extremely limited by bank protection and channelisation. Eaton and Lapointe (2001) compared estimated sediment transport rates for a flood event with a 10-year return period and an event with a 275-year return period on the cobble-bed Sainte Marguerite River in the Saguenay region, Canada. Although sediment rates were higher for the century-scale flood, channel morphology was not significantly impacted by either event, neither at the scale of the channel nor the morphological unit. This is thought to be due to channel modifications in the river in the 1960s, carried out to make space for highway construction. The conveyance of the river was increased as it was channelised, increasing the channel gradient by 50%. In addition, extensive bank protection was installed in 1993, which prevented lateral channel adjustment during the 275-year flood Channelisation usually increases the conveyance of the channel and this may alter channel behaviour downstream.

Channel maintenance

The frequency of in-channel vegetation clearance and/or sediment removal will alter channel capacity and may alter the morphological change caused by a flood event. When sediments and weeds over accumulate in low energy fine sediment systems (for example, rivers in chalk or clay catchments), planned maintenance programmes are generally in place to prevent continuous accumulation. Higher energy systems that experience occasional sediment influx during high magnitude floods are generally subject to ‘breakdown maintenance’ (Sear and others, 1995). However, conventional management often targets the symptom of a sediment problem and neglects the cause (Sear and others, 1995), which can lead to dramatic morphological consequences elsewhere in the system. Hooke and Redmond (1989) question the efficacy of human channel management on active, instable channels, for example, clearing channel bars may increase flow velocities and erosion. Westlake (1975) states that removing plants in densely vegetated channels to reduce flooding may have similar morphological effects to flooding.

The movement of sediment can have a large impact on the ability of a channel to convey floods, but it can also alter the geomorphic features and habitats of a system (Thorne and others, 2011). Flood protection schemes that interrupt sediment continuity to reduce sediment accumulation in the channel to improve flood conveyance can cause channel instability in other parts of the catchment (Sear and others, 2010). Significant flooding occurred in Carlisle in January 2005 and gravel accumulation in the urban reach of the river was identified as a potential factor increasing flood risk (Thorne and others, 2011). However, frequent maintenance would have had severe morphological impacts downstream and the sediment accumulation would likely have reinstated during future flood events. The geomorphological investigation found that the most sustainable action was to allow dynamic upstream reaches to evolve naturally, which would allow them to store coarse sediment, alleviating problems in the urban reach downstream (Thorne and others, 2011). Routinely removing large wood from some fluvial systems could also have morphological impacts, although these impacts are likely to vary depending on location in the catchment. Removing large wood from upstream, smaller channels could cause some forced channel morphologies (for example, pool-riffle) to disappear, and also increase the flood peak and velocities downstream (Wohl and others, 2019).

In-channel structures

In-channel structures such as weirs, culverts and bridges may cause impoundment and sediment aggradation upstream. Scour may occur downstream and around the abutments of bridges. In-channel structures such as culverts and trash screens may get blocked by water-borne items including anthropogenic waste and biotic material such as dead wood. This may cause water levels to back up and the main channel to divert its course.

In-channel structures are represented in the conceptual model of catchment connectivity by Fryirs (2017) (Figure 2.9). Structures such as dams and weirs can reduce catchment connectivity, as sediment is prevented from moving downstream during most flow events. These structures can also reduce the downstream occurrence of floods of higher annual exceedance probability. Therefore, when these switches are ‘turned off’, downstream morphological response to smaller flood events may be reduced. However, during larger flood events, the structures may be breached or bypassed, therefore, turning the ‘switches’ on. In the latter events, large-scale morphological change may occur throughout the downstream reaches of the catchment, as well as upstream knickpoint erosion, which can also occur following weir removal (Hooke and Redmond, 1992).

The impacts of dams on downstream reaches have been well documented. Dam construction can generally cause changes to the downstream discharge and sediment regime, which leads to incision and widening of the channel downstream and fining of the bed substrate. However, the downstream waters are regulated, which means that they are not hydrologically dominated and not particularly responsive to flood events (Castro and Thorne, 2019). The absence of floods can have large-scale effects on the geomorphology and biological communities and assemblages downstream (Jakob and others, 2003). However, geomorphic and biological alterations decrease with distance downstream, as hydrological continuity is restored by tributaries and increased upstream watershed (Ward and Stanford (1995).

Asset failure

During flood events, flood defences may be overtopped, which can trigger bank failure and breaching in some locations, leading to flood plain scour and redeposition of sediment on the flood plain. Where confined by flood defences, high velocity flows may result in channel adjustment during flood events (bank erosion). This may cause damage and/or failure of the defences. Failure of defences increases catchment connectivity; therefore, the extent of morphological change is likely to be wider (Fryirs, 2017).

Asset failure is a risk in modified systems, where the river attempts to equilibrate and morphologically adjust back to a natural state (Death and others, 2015). After a large flood blocked a main road when a channel avulsion occurred on Raise Beck (Cumbria, UK) in 1995, significant channel engineering took place to reduce the impact of future floods on the area. The banks were reinforced to channelise and fix the channel to the north side of the valley. However, Johnson and Warburton (2002) calculated that while these flood protection works will reduce the morphological response of the channel during low and moderate flows, in significant floods (equivalent of the 1995 event) the engineered channel would still be breached, causing sediment and water to spill onto the A591. The condition of bank protection is critical if it is to prevent morphological adjustment. Paine and others (2002) and Gilvear and others (1994) emphasise that the emplacement of embankments over historically active channels may induce failure during large flood events. The periodically active Bloody Inches oxbow on the River Tay was isolated from the main channel by a flood embankment in the 1800s. However, large flows are still capable of inundating the abandoned channel, filling the channel with coarse deposits.

Although regulated flows downstream of dams are generally sheltered from flood events and subsequent morphological change, the extremely rare case of dam outburst flooding may happen where asset failure occurs, which can cause extreme morphological change and threats to life and properties. In 1982, Lawn Lake Dam in Colorado failed, releasing huge amounts of water with peak discharge of 18,000 cubic feet per second down the Roaring River. The river channel was scoured by 50 feet and widened to 300 feet and at the mouth of the river a 42.3 acre alluvial fan was deposited (Jarrett and Costa 1986).

Land use changes

Widespread land use change may cause increased channel sensitivity throughout a large portion of the catchment. Land use changes, which decrease infiltration rates and increase flood plain erosion, such as deforesting for agriculture, may increase the sediment load and deposition in the channel. Human land use change can influence discharge and sediment supply and therefore channel response to large flood events. The impact differs with the distribution and extent of land use change. Land use alteration may be widespread, such as deforestation and the use of land for agricultural fields. In lowland rivers with intensive agriculture on flood plains, reworked soils during overbank floods and soil erosion from run-off dominates the flood plain morphology and contributes large loads of fine sediment into the system. Macklin and Lewin (2003) suggest that during the Holocene (current geological period), British rivers have been variable in their sensitivity to climate change, possibly due to the impact of agriculture on river basin land cover. They found that there was an increase in the number of alluvial sediment flood units after around 4,500 cal. Yr BP, at the same time larger scale agriculture was emerging in the Bronze Age, where trees were cleared to convert to arable fields. This would have increased run-off and sediment supply, increasing the sensitivity of river basin sedimentation to climatic changes.

Changes in forest canopy as a consequence of harvesting or deforestation for agricultural use modifies the peak flow run-off and increases the supply of fine sediment to the channel and subsequent in-channel mobilisation (Stoffel and Wilford, 2011). Figure 2.15 visualises the potential impacts of forest management activities in a catchment. The removal of trees from alluvial fan surfaces can cause surface destabilisation and significant morphological adjustment by downstream channels (Wilford and others, 2003). The effects of the absence of vegetation on fans in the Howgill Fells has been shown to increase gully development and subsequent sediment delivery to the upper catchment during flood events (Harvey, 1998).

Figure 2-15 (a) inappropriate forest management aggravating erosion, (b) in burned areas, reduced soil infiltration, water repellency, removal of surface cover and soil sealing causes increased run-off, (c) erosion on cleared forest floor, from Stoffel and Wildford (2011)

In combination with future climatic changes, land use change may have significant morphological consequences for many catchments. Coulthard and others (2000) modelled a small basin in the Yorkshire Dales, UK to show how decreasing tree cover or increasing rainfall magnitudes caused a 25 to 100% increase in simulated sediment yield, while changing both tree cover and rainfall magnitudes caused a 1,300% increase (Coulthard and others, 2000). This pattern was also observed in a larger basin over longer timescales (9,000 years). Hydromorphological effects may be observed close to the area of land use change but could also be observed throughout the catchment. In the River Swale basin, Coulthard and Van de Wiel (2017) found that deforestation in one half of the basin impacts the other half of the basin. Impacts were more significant downstream of the land use change as deforestation of the basin was shown to increase sediment input over a decade by over 100% (in contrast, reforestation decreased yields by 40%). However, erosion and deposition in the headwaters can also occur as a result of land use change several kilometres downstream, as incision and alluviation cause changes in the valley floor basin.

Urbanisation may increase surface run-off and discharge in the channel, which can cause high rates of downstream bank erosion as the channel adjusts to accommodate higher flows. These effects are usually more localised. Urbanisation increases impermeability of the flood plain, increasing flows and flashiness in a river, which causes heightened morphological response in the downstream reaches of a watercourse. The downstream reach is likely to be hydrologically responsive, potentially similar in behaviour to a river in process domain 2 or 3 (Castro and Thorne, 2019). However, the effects of this will decrease with distance downstream (Hooke and Redmond, 1992).

2.3 Understanding impact of morphological change on future flood hazard assessment

2.3.1 Geomorphological assessment (including Historical Trend Analysis)

A baseline geomorphological assessment is integral to any fluvial study or investigation, providing a detailed understanding of current conditions and processes, including the mapping of key zones in terms of morphological activity (for example, deposition and erosion). The study should provide an understanding of the dynamic fluvial geomorphology of a catchment, as well as a rigorous understanding of the physical processes by which the river channel is formed and alters. While it is critical to understand current morphological processes, a study that includes, or is combined with, an historic trend analysis allows a more comprehensive understanding of historic channel evolution and morphological responses. This can then be used to infer likely trajectories of channel evolution.

Nones (2019) highlights the need to carry out historical geomorphic analyses to help select an appropriate modelling tool, to better understand how the morphology of the river system being studied evolved. This will help to understand the disadvantages of not accounting for sediment transport in flood risk calculations (Brierly and Hooke, 2015). Hooke (2015) listed several practical steps to assess the links between flood risk, flood impacts and channel dynamics.

Developing a historical chronology of river response to changes in the catchment over time provides context on why the system is in its present state, identifying key historic and contemporary pressures. This helps to predict how the river system is likely to develop under a range of different pressure scenarios in the future. Sustainable management advocates giving rivers the freedom to move and not constraining this natural process of movement; solutions to further constrain river flows only build up problems for the future. Consequently, by mapping changes in channel planform and morphological characteristics over time, predictions of future channel change can more easily be determined.

Changes to a river are a function of both local controls on flow pattern and energy concentration and other wider catchment controls on flow magnitude, frequency and sediment transport, and it is particularly notable that there are seasonal differences that affect processes and flood risk (Hooke, 2015). Figure 2-16 outlines the principal controls on reach-scale channel morphology, highlighting the importance of existing hydromorphological conditions, human influences and historic trends at both the local and catchment scales. It is therefore evident that future channel evolution predictions need to consider both local and catchment controls on the river system and how these may change/influence fluvial system dynamics; consideration should also be given to seasonal changes in terms of vegetative influence over hydraulics and processes (Hooke, 2015).

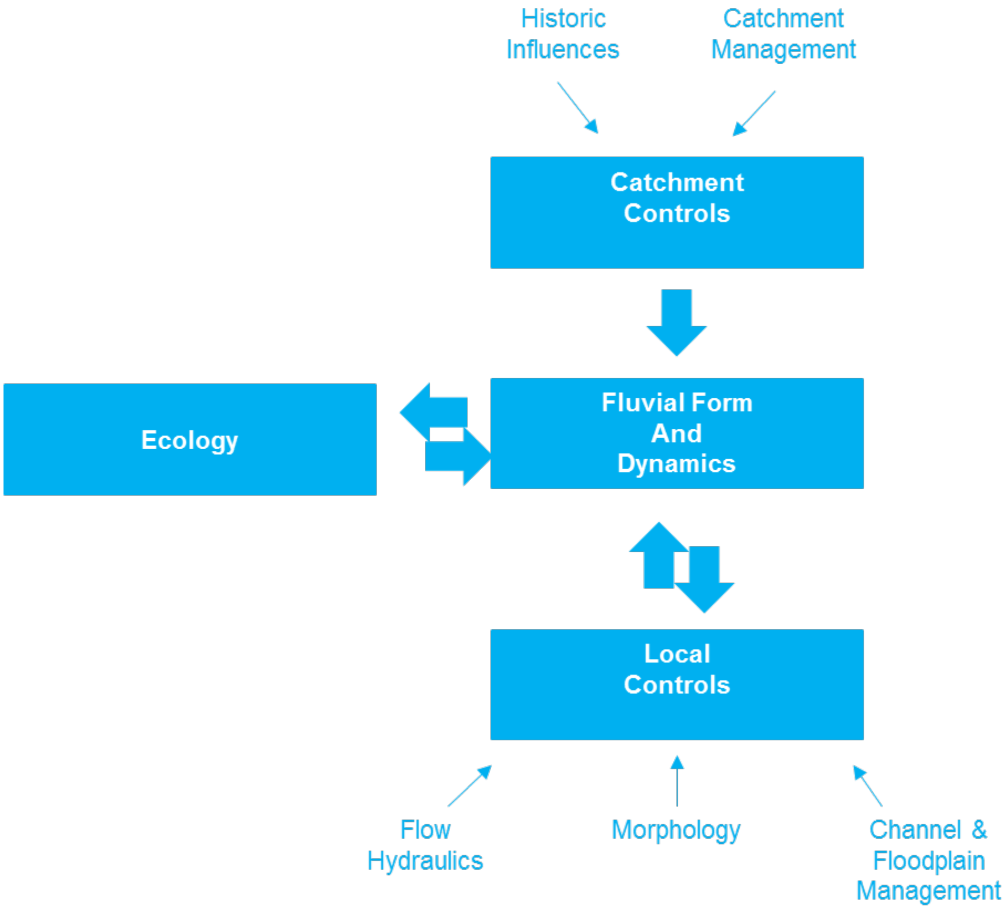


Figure 2-16 Principal controls on the character and dynamics of fluvial systems

By considering all the controls on system functioning, including the existing geomorphological processes operating at the reach scale, the most active channel zones can be mapped in order to focus the assessment of future channel change and flood hazard predictions.

There are a number of different assessment methodologies available to investigate geomorphological processes at a reach or catchment scale that either encompass, or can be used alongside, an historic trend analysis to infer likely trajectories of channel evolution. These include:

- catchment baseline survey (Environment Agency, 1998) – provides a strategic overview of the geomorphological state of the rivers throughout the study catchment
- fluvial audit (Sear and others, 1995) - a methodology for carrying out a geomorphological survey that synthesizes historical data on the catchment land-use and channel network, with contemporary morphological maps to present a statement of the location and type of sediment supply, transport and storage within the river basin
- river reconnaissance survey (Thorne, 1998) – a rapid geomorphological survey of a reach, noting the contemporary morphological forms and identifying the predominant geomorphic processes
- geomorphic dynamics assessment (Sear and others, 2004) – provides a detailed, intensive, small-scale assessment of the channel in a problem reach (identified through a catchment baseline survey or fluvial audit). The assessment provides quantitative guidance on stream power, sediment transport and bank stability processes
- In addition, Hooke (2015) suggests several practical steps when considering how geomorphological changes may affect flood risk. She suggests that checks are made into (a) existing morphology (hydraulics, resistance, seasonal range in reach response to flooding); (b) the flood that affects channel morphology; (c) the most recent large flood; (d) evidence of longer-term trajectory of the reach; and (e) sediment supply, connectivity and channel stability before assessing potential changes from flooding.

The use of historical sources, maps and other documents for analysing channel planform change has been advocated for a long time (Hooke, 1977; Hooke and Kain, 1982; Hooke and Redmond, 1989). Historic mapping can also be used for determining the rate of channel adjustment, as well as the influence of human activities (Skinner and Thorne, 2006; Hooke, 2007; Hooke and Yorke, 2010).

However, historic geomorphic analyses can be time consuming and require manual intervention, an approach that is not always appropriate or economical at larger spatial scales, for example, across whole countries. In these larger scale projects, a quicker, more automated method is required, where readily available catchment-scale information is used to prioritise geomorphological processes in flood risk management.

It is therefore important that risks arising from sedimentation and erosion are assessed and incorporated into flood risk management to mitigate the potential impacts of flooding on the economy, environment and human health.

It should be noted that historic trend analysis assumes that hydrological processes are stationary. However, a substantial body of research shows that the frequency of hydrological extremes has been changing and is likely to continue to change in the near future (Bayazit, 2015; Šraj and others, 2016). In a changing world, decision making in water resources management requires long-term projections of hydrological time series that include trends due to human intervention and climate change (Bayazit, 2015).

2.3.2 Flood hazard and flood risk

Morphological change can impact on flood hazard and flood risk. Flood risk is a combination of the probability (likelihood or chance) of an event happening and the consequences (impact) if it occurred. Flood risk is commonly defined as the product of hazard, that is, the physical and statistical aspects of the actual flooding (for example, return period, extent and depth of inundation, and flow velocity), and the vulnerability, that is, the exposure of the people and assets to floods and the susceptibility of the elements at risk to suffer from flood damage (Sayers and others, 2003 and Apel and others, 2009 cited in Vojtek and Vojteková, 2016).

The Directive 2007/60/EC on the Assessment and Management of Flood Risk (from now on called EU Floods Directive 2007) (no longer in effect in England from 01 January 2021) aims to reduce and manage risks that floods pose to human health, environment, cultural heritage and economic activities. The EU Floods Directive states that member states must implement flood hazard and flood risk maps. Flood hazard maps are produced for a range of flood event scenarios, commonly depicting flood extent, water depth/level and flow velocity (Figure 2-17). Flood risk maps are produced to show the potential adverse consequences associated with a range of flood event scenarios (Figure 2-18). Commonly, these are expressed in terms of the indicative number of inhabitants and type of economic activity potentially affected, as well as other information that member states consider useful. This includes indicating areas where floods with a high content of transported sediments and debris floods can occur. High sediment delivery can increase flood risk by reducing the channel capacity following sedimentation or by altering the river planform.

Risk maps are mostly derived from single design floods that represent a hazard based on a specified return period. It is implicitly assumed that morphology will not change during flood events or by long-term erosion or deposition. However, it is obvious that the river bed elevation can change quickly and drastically (Neuhold and others, 2009). This is explored further in the following sections.

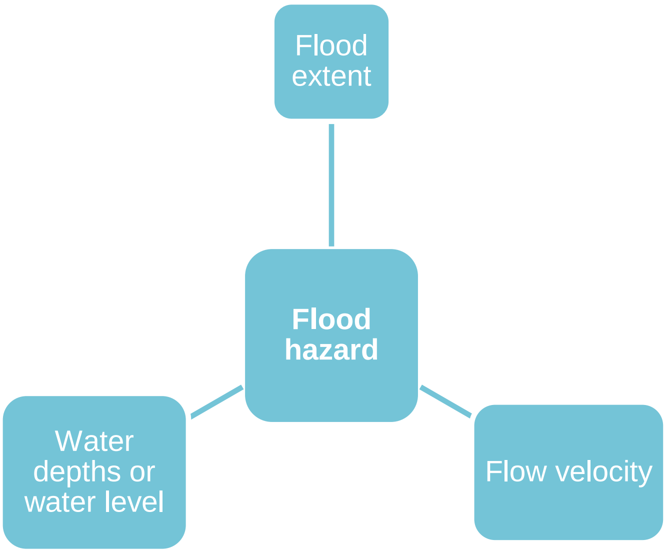


Figure 2-17 Common flood hazard mapping outputs

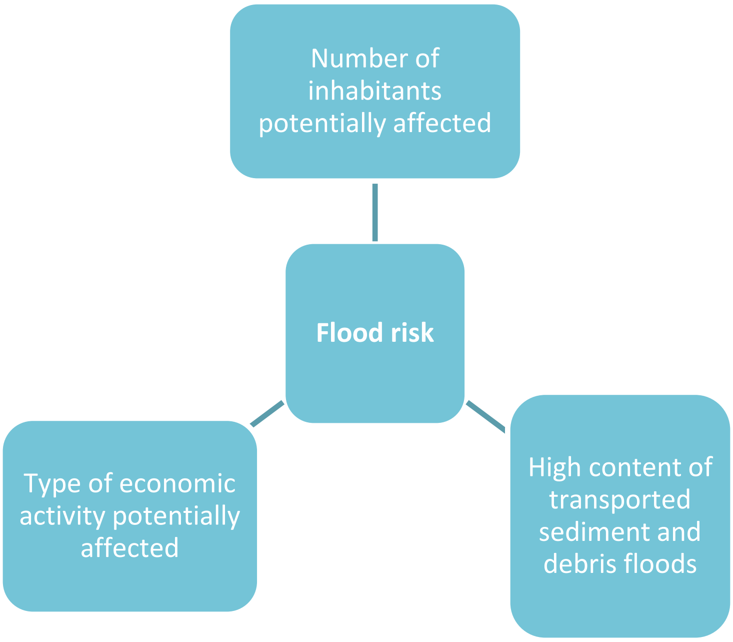


Figure 2-18 Common flood risk mapping outputs

2.3.3 The impact of morphological change on flood hazard

Slater and others (2015) state that a change in the frequency and areal extent of flooding can be caused by one of two factors: a change in the frequency of high flows (the ‘flow frequency effect’), and/or a change in the capacity of the channel to contain floods (the ‘channel capacity’ effect). River channels and flood plains in the UK are dynamic, responding to changes in frequency and magnitude of floods, and to variations in the size and amount of sediment they transport (Macklin and Harrison, 2012). Lane and others (2007) showed that 16 months of measured in-channel sedimentation in an upland gravel-bed river caused about half of the increase in inundation extent that was simulated.

More recently, Nones (2019) summarised that morphological change and sediments moving in rivers impact the flood frequency and can increase it through the following:

- reduction of the channel capacity (Slater and others, 2015)
- morphological adjustments in response to a variable sediment supply from upstream (Lane and Thorne, 2007)
- bed aggradation and erosion due to damming and backwater effects (Maselli and others, 2018)

Higher water velocities during flood events often cause increased lateral and vertical erosion within the river channel, resulting in a wider and deeper channel that is more efficient for conveying flood flows. Therefore, channel capacity may be increased through channel enlargement, which can also decrease flood risk.

Multi-directional interactions exist between geomorphology and vegetation, which can ultimately impact flood frequency. For example, newly exposed sediment deposits can result from a large flood event, which may become colonised by vegetation over time, dependent on the sequence of flows following the initial flood event. The presence of vegetation reduces channel capacity and increases channel roughness, which promotes further sediment accretion as well as increasing the potential for transported material to get trapped and block the channel. This may increase future flood frequency and indeed may have a bigger impact on flood risk than the deposited sediment.

Nones (2019) highlights that flood risk studies are often connected to extreme hydrological events, assuming only clear water and non-erodible channels when carrying out hydraulic modelling to prepare flood risk mapping. However, geomorphic processes, human alterations and management practices can alter a river's geomorphological response to flooding events. Nones (2019) also emphasises the difficulty of incorporating and schematising the spatial interactivity of rivers, long-term morphological changes and sediment-related processes into hydraulic modelling approaches. This is often exacerbated by a lack of detailed sedimentological data on both bedload and suspended load that is needed to accurately calibrate morphodynamic models.

2.3.4 Data sets to identify morphological change on flood hazard

Several national data sets are available to assess the likelihood or consequences of fluvial flooding. In many locations, these are supplemented by more detailed, local hydraulic modelling studies.

Methods for predicting channel change range from detailed geomorphological studies (together with an historic trend analysis) to hydraulic modelling studies. These methods rely on a wide range of data sources. Historic maps and aerial imagery can be used to carry out an historic trend analysis. Hydraulic modelling studies rely on detailed channel cross section survey and/or LiDAR data. Some of the more detailed modelling approaches require sediment size information.

Monitoring surveys, which are repeat surveys taken at the same location over time, can be particularly valuable. These methods can be used to measure erosion and/or deposition rates and infer future change over both short and long timescales. A full review of available methods is outlined in 'Geomorphological Monitoring Guidelines for River Restoration Schemes' (Environment Agency, 2007). In summary, the following monitoring methods can provide a valuable resource for understanding and/or quantifying geomorphic processes (erosion and deposition) and predicting channel change when repeat surveys through time are available:

- Ground photography - provides a visual representation of change at a site, with photographs taken at a series of fixed locations. Ground photography can be carried out at various times, but it is recommended that it should be taken at regular intervals, with additional sets after high flow events.

- Aerial photography - carried out using drone survey equipment and provides a visual representation of change at a site. Can be carried out at regular intervals, similarly to ground photography.

- Channel cross section survey – carried out to record channel adjustment at particular locations over time. Recording cross sections is an objective and repeatable methodology that provides quantitative data on the level of deposition and erosion that has occurred between surveys. If carried out at regular intervals, and after high flow events, it can be used to quantify channel change. It is limited however by the fact that it only provides an estimation of change at fixed moments in time and cannot quantify changes between these periods. This means that fluctuations in deposition between the survey dates are not accounted for.

- Topographic survey - provides the x, y and z coordinates of key points that will enable a digital terrain model of the river and its flood plain to be constructed. A detailed resolution survey is required if adjustments over time are to be documented though repeat surveys. Fixed markers within the survey extent are required to enable repeat surveys to be carried out.

The LiDAR data based tool ‘SEAL’ (Surveillance of Embankment Assets with LiDAR) has recently been produced by the Environment Agency. This combines LiDAR data, flood asset data and 1880s mapping and can be used for desktop studies to complement the site visits required for a baseline geomorphologic assessment.

Setting up monitoring programmes to repeatedly collect this information at hotspots of erosion and deposition is recommended to provide baseline information and quantify rates of change. As such, any existing data sets like this could be reviewed before detailed hydraulic modelling is carried out.

2.4 Summary

The literature review for this study has found that the morphological impacts during flood flows can vary spatially throughout the catchment, but also with time, as a result of flood sequencing. Morphological changes can occur gradually, as a result of evolutionary adjustments, suddenly, in response to high magnitude events, or in response to lower magnitude events if the system is close to a geomorphic threshold. River morphology is highly dependent on the limits imposed by boundary conditions (geology), while the width of the band of ‘expected capacity of adjustment’ is controlled by flux boundary conditions (interactions between water, sediment and biota).

Human modifications to the channel or flood plain may disrupt longitudinal and lateral connectivity, which can cause widespread alterations to the ‘expected capacity of adjustment’, triggering behavioural changes and associated changes in river morphology. These boundaries set the process domain and the range of river morphologies that are likely to occur, as well as their response to disturbance events such as floods. Although flooding and morphological adjustment are natural fluvial processes that underpin many vital ecosystem services, flood-induced morphological change can increase future flood hazard if it is near to infrastructure or properties. Lane and others (2007), for example, concluded (as reported in the Pitt Review) that changing channel capacity may be the dominant driver of flood risk in the first half of this century. They made it clear that it is important to account for these changes.

In summary, morphological change in response to flood events:

- depends on geological factors, such as the degree of valley confinement which is most extensive in the upper catchment
- varies with the scale and sequencing of the flood
- is broadly scaled by stream power relative to erodibility of channel margins
- depends on lateral and longitudinal connectivity in the catchment, which determines the extent of impacts
- is therefore affected by both in-channel and flood plain modifications

The sensitivity of a channel to geomorphological change is strongly influenced by its location within a catchment as this governs the process domain which in turn determines the channel type and how this responds to floods (Figure 2-13).

Table 2.4 summarises main influencing factors identified from the literature review.

Table 2.4 Morphological responses and main influencing factors from the literature review

Influencing factor	Morphological responses
Bedrock/ valley confinement	Research (for example, Hooke and Redmond, 1989) suggests that adjustments of the lateral planform are concentrated in the margins of the uplands, where rivers are downstream of the upland bedrock reaches and flow through coarse erodible alluvial deposits (although sensitivity varies from river to river and reach to reach). Stream gradients here are relatively steep, creating high stream power and erosive conditions during higher magnitude flood events. Similarly, confined channels may be relatively unresponsive to large flood events, but can cause major geomorphic change in reaches upstream and downstream (Dean and Schmidt, 2013). Therefore, potential hotspots of channel change could occur downstream of bedrock/confined areas in piedmont areas (the margins of upland areas) where coarse, erodible alluvial deposits are present.
Channel slope (natural)	Channel slope can be used to identify areas that are steep with erodible alluvial deposits and a lack of stabilising riparian vegetation. This link to an understanding of the geology and riparian vegetation cover is crucial, since these factors will significantly alter channel stability and the sensitivity to change.
Sediment supply and connectivity	The rate of sediment supply and resulting channel response to flood events depends on the activity of sediment sources. Systems with a high supply of sediments (such as those sourced from river bank erosion, eroding valley sides, unstable mine workings and landslides) have been found to be sensitive to channel change during high flows. In some cases, high flows in such systems have caused stable single thread channels to change to multi-threaded forms (Harvey, 2001; Warburton and others, 2002).
Large wood and riparian vegetation	Vegetation in the riparian and flood plain zones can have a stabilising effect on geomorphic processes. Riparian vegetation has the most significant influence in lower gradient, laterally unconfined reaches, where vegetation increases the cohesion of riverbanks (Buffington and Montgomery 1993), making them less sensitive to morphological change during flood events. During large flood events, overbank flows may be attenuated by riparian woodland, causing the deposition of transported sediment on the flood plain. This reduces the likelihood of changes to the channel network (for example, channel avulsion) in response to elevated levels of erosion or deposition within the channel (Stoffel and Wilford, 2012). The effect of large wood on channel morphology and response depends on channel size (Marcus and others, 2002), as well as the presence of riparian vegetation (as discussed above). In smaller channels, large wood remains in situ except for during higher magnitude flow events as it is generally too large to be mobilised, while in larger channels large wood is flushed out by regular flows. Large flow events have the capacity to (re)distribute large wood throughout the catchment, strip vegetation from the flood plain (Magilligan and others, 2015) or undercut riparian trees as channel banks rapidly erode. Trees transported downstream in flood events can block bridges and structures in larger rivers, which can have a proportionately greater morphological impact. During the Lynmouth Floods of 1952, log jams were highlighted as the cause of the flood waves (Green, 1955).
Flood plain infrastructure	Modifications to flood plain-channel connectivity can have significant consequences on channel response to flooding (Montgomery and Buffington 1993). Infrastructure on flood plains can restrict and confine morphological adjustment of rivers during flood events. This may cause channel widening/bank erosion in these confined areas, which can undermine structures. Whereas the river would have previously overspilled onto the flood plain during over bank flows, flood flows are now artificially contained

Influencing factor	Morphological responses
	within the channel. Therefore, increased stream power in artificially confined reaches may cause bed scour and incision, which further increases the confinement of the channel and the transport capacity of the channel (Joyce and others, 2018; Death and others, 2015). The impacts of channel modification on morphological response to floods may be more visible downstream. Joyce and others (2018) found that although erosion of the channel bed and banks occurred in upstream artificially confined areas, extensive overbank deposition occurred in unconfined downstream reaches, where flow velocities were dissipated over the flood plain.
Channel modification	Channel modifications (such as channelisation, straightening and realignment) often involve alteration of the cross section, such as narrowing, widening or deepening. These alterations may cause channel degradation upstream of the modified reach, which is exacerbated during flood events. This is where channel bed incision and bank undercutting occur, which steepen the banks and make them prone to bank failure, further widening the channel. Floodwaters are quickly conveyed downstream, therefore, the channel response to floods may be more visible downstream. Eroded sediments may be deposited in downstream reaches. If deposited sediment forms a plug, channel avulsion may occur as the channel attempts to morphologically adjust back to its natural state. Water that spills onto the flood plain may flow in palaeochannels.
Channel maintenance	Occurrence and frequency of in-channel vegetation clearance and/or sediment removal will alter channel capacity and may impact the potential morphological change caused by a flood event. Conventional management often targets the symptom of a sediment problem and neglects the cause (Sear 1995), which can lead to dramatic morphological consequences elsewhere in the system.
In-channel structures	In-channel structures such as weirs, culverts and bridges may cause impoundment and sediment aggradation upstream. Scour may occur downstream and around the abutments of bridges. In-channel structures such as culverts and trash screens may get blocked by large wood. This may cause water levels to back up and the main channel to divert its course. Structures such as dams and weirs can reduce catchment connectivity, as sediment is prevented from moving downstream during most flow events. These structures can also reduce the downstream occurrence of floods of higher annual exceedance probability and downstream morphological response to smaller flood events may be reduced. However, during larger flood events, the structures may be breached or bypassed and large-scale morphological change may occur throughout the downstream reaches of the catchment, as well as upstream knickpoint erosion (Fryirs, 2017).
Asset failure	Where confined by flood defences, high velocity flows may result in channel adjustment during flood events (bank erosion). This may cause damage and/or failure of the defences. Failure of defences increases catchment connectivity, therefore, the extent of morphological change is likely to be wider (Fryirs, 2017). During flood events, flood defences may be overtopped, which can trigger bank failure and breaching in some locations, leading to flood plain scour and redeposition of sediment on the flood plain. Asset failure is a risk in modified systems, where the river attempts to equilibrate and morphologically adjust back to a natural state (Death and others, 2015). The condition of bank protection is critical if it is to prevent morphological adjustment. Paine and others (2002) and Gilvear and others (1994) emphasise that the emplacement of embankments over historically active channels may induce failure during large flood events.
Land use changes	Widespread land use change may cause increased channel sensitivity throughout a large portion of the catchment. Land use changes that decrease infiltration rates and increase flood plain erosion, such as deforesting for agriculture, may increase the sediment load and deposition in

Influencing factor	**Morphological responses**
	the channel. Human land use change can influence discharge and sediment supply and therefore channel response to large flood events. The impact differs with the distribution and extent of land use change. Land use alteration may be widespread, such as deforestation and the use of land for agricultural fields. In lowland rivers with intensive agriculture on flood plains, reworked soils during overbank floods and soil erosion from run-off dominates the flood plain morphology and contributes large loads of fine sediment into the system. Changes in forest canopy as a consequence of harvesting or deforestation for agricultural use modifies the peak flow run-off and increases the supply of fine sediment to the channel and subsequent in-channel mobilisation (Stoffel and Wilford 2011). The removal of trees from alluvial fan surfaces can cause surface destabilisation and significant morphological adjustment by downstream channels (Wilford and others, 2003, Harvey, 1998). Urbanisation may increase surface run-off and discharge in the channel, which can cause high rates of downstream bank erosion as the channel adjusts to accommodate higher flows. These effects are usually more localised.

3 Review of flood events

3.1 Overview

This section reviews the existing available data for the following 5 flood events: 2005, 2007, 2008, 2009, and 2015 to 2016. The cause of each flood event is examined, as well as the morphological channel changes that occurred in response to the flood, and any flood impacts that resulted from those morphological changes. A summary of the causal and/or exacerbating factors, the types of geomorphological changes, and the consequential flood impacts for each flood event is presented in section 3.7.

The data used in this report comes from a variety of flood investigation and fluvial audit documents, as well as online sources. Information was provided for the Kent and Wharfe catchments, as well as a wider range of catchments impacted by these flood events.

The flood events selected were chosen because they resulted in significant morphological changes that have been well documented. They occurred in predominantly upland basins with ‘active’ gravel-bed rivers typical of process domains 2 and 3. Other floods that also caused significant morphological changes, such as those in the Winchester (2013), Thames (2014) and Somerset (2013 to 2014) regions, could be also investigated to understand how specific controlling factors operate in lowland catchments (domain 4).

3.2 2005 flood event

3.2.1 Background

In January 2005, a major flood occurred in Cumbria, when 2 months’ worth of rainfall fell in 24 hours (Geographical Association, ‘What was the hydrology of the January 2005 flood’). The rain fell on ground that was already close to saturation due to above average rainfall and flooding during December 2004. In the River Kent, the December flood event peaked at Burneside, Cumbria on 6 to 7 December 2004, at a level reported to be around 200 mm higher than that measured in Kendal during the previous flood of February 2004 (Cumbria County Council, 2016c). High levels of previous soil saturation caused excessive conversion of rainfall to surface run-off during the 2005 event. Consequently, water levels in a number of Cumbrian rivers (including the Kent, Eden and Derwent) rose rapidly. The 2005 flood peaked in the upper parts of the Kent, Eden and Derwent catchments in the early hours of 8 January.

Further downstream in Carlisle, the River Eden peaked at an estimated 1,520 m^3/s at the Sheepmount Gauging Station at 2.30pm on 8 January. This flow has a return period of around 175 to 200 years (0.57% - 0.5% AEP). At other locations, the return period was shorter, but still in excess of 50 years (2% AEP). A notable feature of this event was that flooding was initially caused by surface water flows that overwhelmed local drainage networks, with river flooding occurring at upstream locations such as Appleby. The flood wave then progressed downstream and into Carlisle, where it overtopped flood defences along the River Eden, flooding a large number of homes and businesses, as well the Civic Centre and the Police Station (Environment Agency, 2006).

3.2.2 Morphological responses

Significant amounts of erosion and deposition (typically gravels) occurred along the main Cumbrian rivers and their tributaries. At a number of locations, erosion and deposition caused minor changes in the planforms and courses of some rivers as well as aggravating flood damage to roads and other infrastructure (Jacobs, 2007). This was particularly the case along the River Caldew, which is a tributary of the River Eden that confluences within the city (Figure 3.1), and the Caldew and Carlisle City Flood Alleviation report provides a detailed examination of morphological response to the 2005 flood event in the River Caldew.

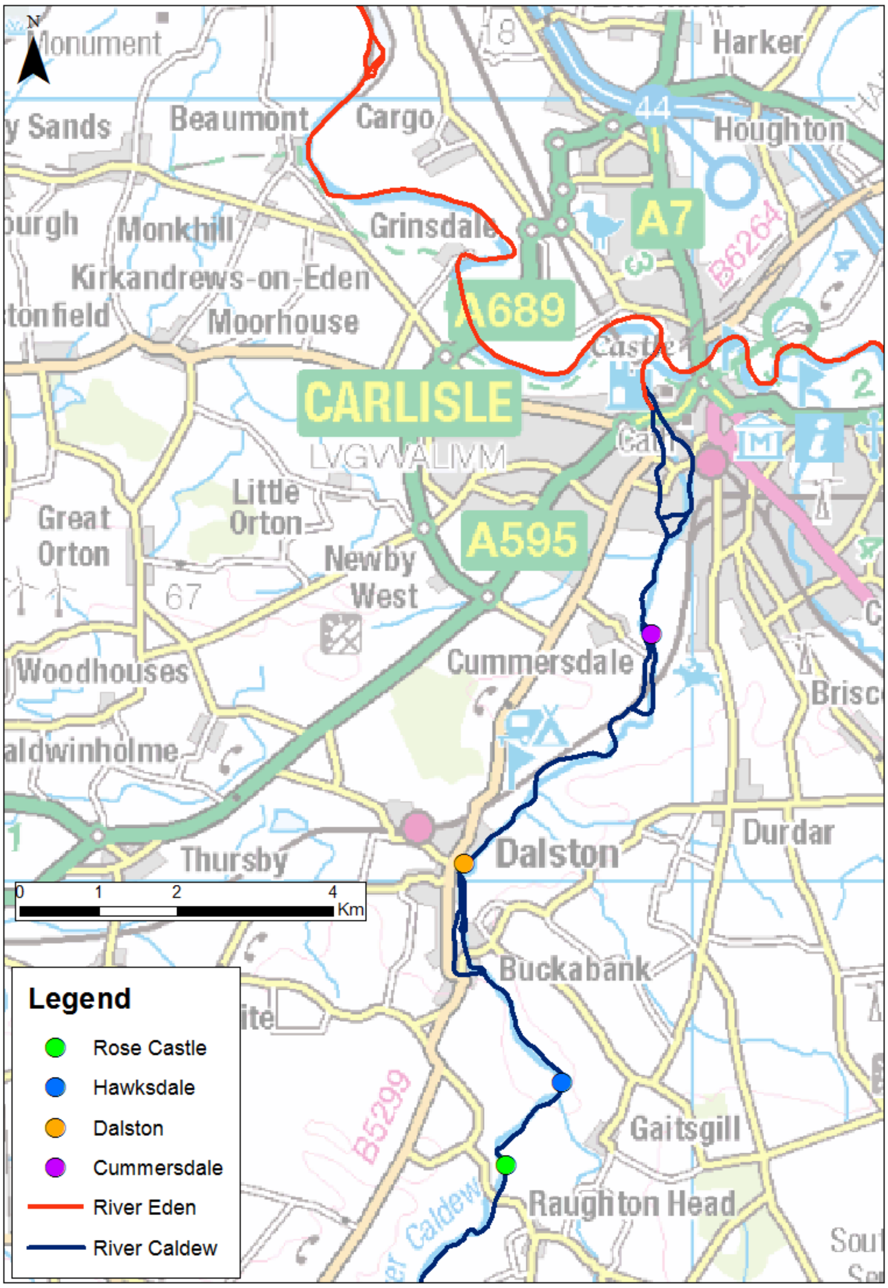


Figure 3-1 Location of the River Caldew, main areas of geomorphological activity are indicated (Rose Castle, Hawksdale, Dalston, Cummersdale)

River Caldew

Overall, the 2005 event did not lead to significant widespread changes in channel planform, such as switches from a single thread to braided patterns. It did, however, cause severe, localised bank erosion and sediment deposition. In some places, several metres of bank retreat occurred, while old sediment features were reworked and new sediment, supplied from upstream, was deposited.

Significant erosion mostly occurred on the outside banks of meander bends, while deposition occurred on the inside of bends. This effect was further accentuated as flows were deflected towards the opposite bank by deposited sediment, increasing erosive velocities and shear stresses. In straighter reaches, basal scour led to banks collapsing and trees falling. This, in turn, caused the channel to widen and sediment to be deposited locally and upstream.

At Rose Castle, Hawsksdale, Dalston, Cummersdale and Carlisle Crematorium, the channel of the River Caldew is well connected to its flood plain and preferential flow routes for overbank flows include palaeochannels, low terraces and vegetated former bar surfaces. In these reaches, the paths followed by overbank flows during the 2005 event could be identified by deposits of gravels and cobbles.

The most significant channel morphological changes occurred in the following locations:

- Hawksdale (Figure 3.2) – bank erosion was most significant where trees had fallen, either before or during the event. Large amounts of sediment deposition at this location also deflected flows to cause increased bank erosion, which was noted to have slightly increased channel sinuosity in the reach.
- Former Cummersdale Weir (Figure 3.3) – reorganisation of in-channel deposits occurred at this location. Sediments deposited in the impounded zone immediately upstream of the weir, resulted in a bypass channel that had been present before 2005 becoming the main channel conveying all flow. Downstream, sediments were reactivated as a point bar was cut through by migration of the main channel.
- Upstream of Holme Head Weir (Figure 3.4) – sediment deposition caused several metres of bank retreat.

The flood significantly increased the extent of active sediment deposits in the channel, both through the reworking of old surfaces and the formation of new features by deposition of sediment supplied from upstream. This suggests that low frequency, high magnitude events are an important control on channel morphology, although they are not the only influence. It is also suggested that the morphological impact of the 2005 flood event was made worse by previous activity: the events of February and December 2004 having brought additional sediment into the fluvial system of the River Caldew. This supports the general theory that closely spaced floods can increase morphological response expressed through both in-channel sediment activity and channel migration.

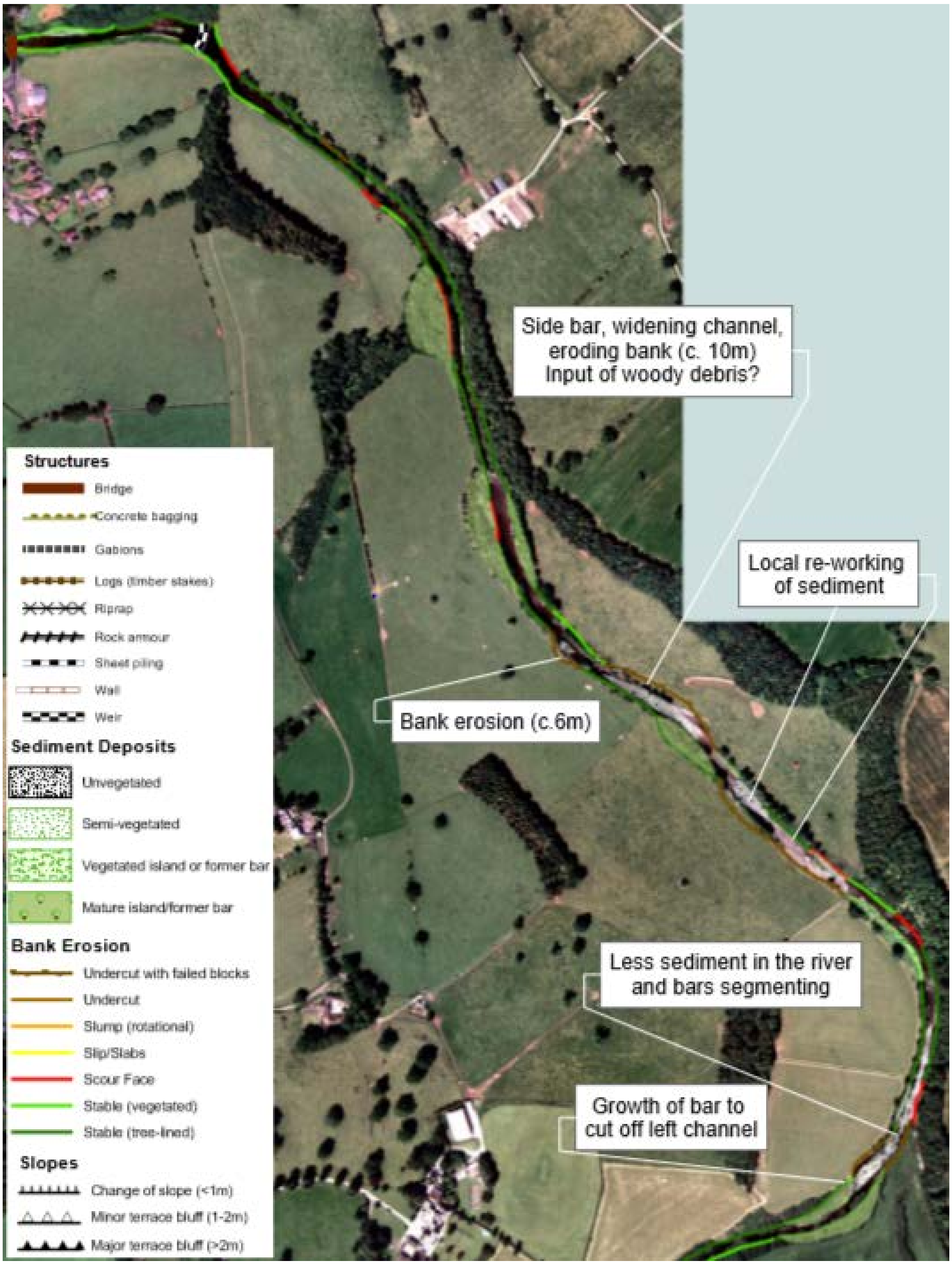


Figure 3-2 Post flood (2005) change at Hawksdale, from Jacobs (2007)

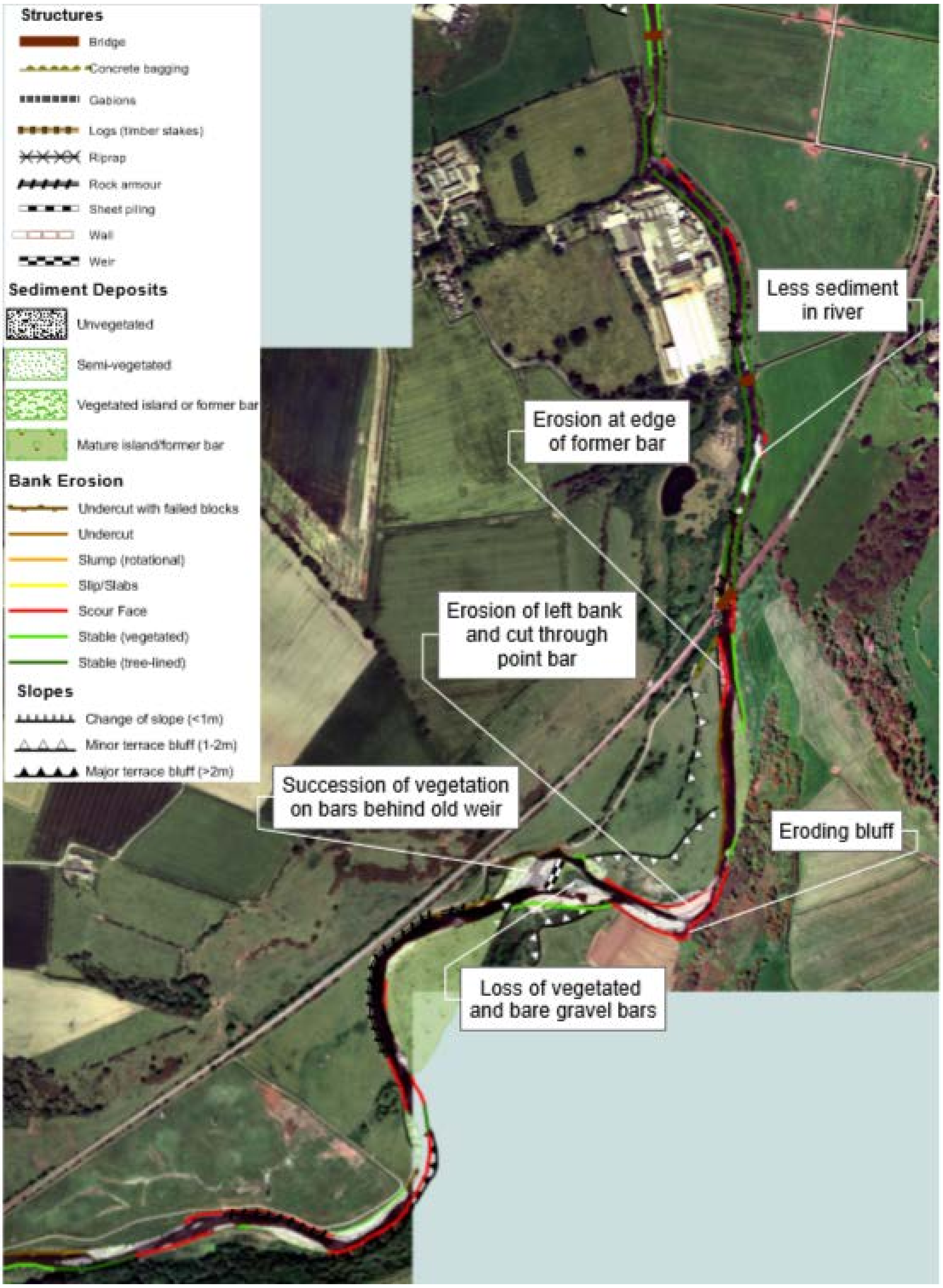


Figure 3-3 Post flood (2005) change at the former Cummersdale weir, from Jacobs (2007)

Figure 3-4 Post flood (2005) change upstream of Holme Head weir, from Jacobs (2007)

River Kent

Damage caused by the January 2005 event was also recorded in the River Kent. The Burneside Flood Investigation Report (Cumbria County Council, 2016a) documents these at various locations in Burneside. Flooding affected several properties in the Carling Steps area, and overtopping of defences upstream of Ford Bridge was attributed, in part, to the bridge being partially blocked by a tree lodged against the structure. Similarly, the Cumbria Floods Technical Report (Environment Agency, 2006) records that the first area to be affected during this flood event was Burneside, upstream of Kendal, where the river overtopped its banks upstream of New Road Bridge and bypassed the bridge. In total, 9 properties flooded upstream of the bridge, with the general depth of flooding around 300 mm. A tree was later found to have lodged against the bridge, which may have led to the floodwater coming out of bank. These examples illustrate the risks of exacerbated flood damages due to blockages following large wood entering the water due to bank erosion/undermining during a flood event.

3.3 2007 flood event

3.3.1 Background

Background information on channel changes resulting from the summer floods in 2007 is relatively scarce in the supplied documentation, as well as online.

The summer floods of 2007 occurred in 2 major events; the first in June and the second in July. In June 2007, the majority of the UK experienced well above average rainfall and, for some areas in Yorkshire, it was the wettest June on record, with widespread flooding reported throughout the latter half of the month (Met office, ‘June 2007’). Record July rainfall totals and heavy rainfall on 19 to 20 July resulted in widespread flooding across the south Midlands (Met office, ‘Heavy rainfall/flooding – July 2007’). These floods were so damaging that they prompted the Pitt Report of 2008, which, in turn, led to the Flood and Water Management Act of 2010. This Act introduced the policies of natural flood management and Working with Natural Processes. Therefore, while the morphological changes caused by the 2007 flood events are poorly documented, the floods were pivotal in changing the direction of flood and coastal erosion risk management in the UK.

3.3.2 Morphological responses

As described above, the morphological responses to the 2007 flood event are poorly documented. A culvert in Kell Beck in Otley was blocked by fallen trees, which diverted the course of the River Wharfe into neighbouring fields. Heavy rain poured off the moors, blocking the road between Menston and Bingley in at least 5 locations (Ilkley Gazette, 2005). The cricket ground was flooded in Ilkley and part of the pitch was scoured away.

3.4 2008 flood event

3.4.1 Background

Sudden and severe flooding occurred in the Breamish and Till catchments (Northumberland, England) and Bowmont Water (Scotland) over the weekend of 6 to 7 September 2008. Flooding occurred after prolonged heavy rainfall due to a slow-moving, low pressure weather system, following several weeks of above average rainfall. At Chillingham Barns weather station in the Till Valley near Chillingham, rainfall for the period 4 to 6 September totalled 158.3 mm, equivalent to 290% of the September average for this location. This was provisionally estimated as equivalent to a 1 in 200 year event (0.005 AEP) (Met office, 'Heavy rainfall early September 2008'). The severity of the flooding in the Breamish and Till catchments was due to the combination of the high magnitude of the event, localised flood bank failure in the Till and Glen river systems and the low relief topography of the Breamish and Till flood plains (Oughton and others, 2009).

3.4.2 Morphological responses

Rivers Till, Breamish and Glen

The Cheviots Flood Impact study (Oughton and others, 2009) details the morphological responses of rivers in the Cheviots to the September 2008 flood event. Near or complete overtopping of flood defences was widespread in the Till catchment, and in many locations this triggered localised failure and breaching of flood banks. Flood bank failure frequently occurred at the apex of abrupt river bends, or where embankments crossed topographic depressions reflecting the course of abandoned former channel courses. Breaching was often associated with marked scouring of the flood plain surface at the breach site and redeposition of excavated sediment as extensive spreads of sand and gravel immediately beyond the breach (Figure 3.5).

Large-scale bank erosion (locally exceeding 40 to 50 m) occurred in several areas in the Breamish study reach (Oughton and others, 2009). The Brandon-Ingram road was undermined and bridge abutments were damaged at Ingram and Brandon. The most severe bank erosion in the River Breamish occurred in a 1 km reach centred on Brandon footbridge and ford. In this location, the present river occupies an man-made confined flood plain corridor, which promotes relatively deep flood flows, and where the channel banks tend to comprise thick sequences of 19th and 20th century alluvial sand and gravel (Figure 3.6). Erosion in this location threatened the road, ford and footbridge as well as an electricity pylon on the south bank.

Floodwaters from the Breamish also locally altered the flood plain between the Visitor Centre and Ingram Mill. Overspill here occurred as a result of gravel deposition in the channel bed near the Visitor Centre car park and breaching of the gorse barrier on the left bank. This may have promoted a localised change in channel course and configuration if left unmodified. In both locations, breaching of the embankment and re-routing of flows triggered scouring of the flood plain surface and redeposition of sands and gravels immediately beyond the breach.

Figure 3-5 Flood scour and gravel deposition associated with overspill of the River Glen near Kirknewton, from Oughton and others (2009)

Figure 3-6 Site of major bank erosion during the September 2008 flood – north bank of the Breamish downstream of Brandon Ford, from Oughton and others (2009)

Localised changes in the river course (‘avulsion’) took place in the River Glen at Kirknewton (Oughton and others, 2009). A new channel routed across the southern part of the valley floor when overspill occurred following a major breach in the embankment, creating a crevasse-splay depositional feature on the flood plain (Figure 3.7). Floodwaters flowed in palaeochannels on the flood plain, flowing back into the main channel 900 m downstream near Lanton. In Figure 3.7, the intact embankment can be seen to prevent overbank flow from returning to the main channel in the next field downstream of the breach. Instead, flood water continued along the flood plain for a much greater distance, artificially extending the scale of the morphological response.

Figure 3-7 Embankment breach and changed course of the River Glen at Kirknewton (before reinstatement of channel in pre-event course to left, from Oughton and others (2009)

Wooler Water

The flood event of September 2008 also resulted in significant geomorphological adjustment in the Wooler Water (Northumberland), involving channel enlargement (deepening and widening) and the creation of a very large number of additional sediment sources and channel deposits (Jacobs, 2011). The 2008 event triggered catchment-wide activation of geomorphological processes and can therefore be considered a threshold event. A second large flood event in 2009 (with an almost identical peak water level, but of shorter duration) led to further bank erosion and reworking and further build-up of channel deposits. The impacts of both flood events, and the main controls on channel process and form are discussed further in section 3.5.2.

3.5 2009 flood events

3.5.1 Background

Extensive flooding occurred in Northumberland on 18th July 2009 and in Cumbria on 19th November 2009. Flooding affected numerous catchments, including Wooler Water (July) and the Derwent, Cocker, Kent, Eden and Eamont (November). In the River

Derwent catchment, the flood was a very significant event, well in excess of the 1% annual exceedance probability flow (100-year flow) and the highest then on record. Seathwaite in the Derwent catchment received 316 mm of rain in 24 hours on 19 November, which was then a UK record for any 24-hour period (Met office, ‘Heavy rainfall/flooding in the Lake District’). In the Kent catchment, a maximum flow of 268 m^3/s at the Victoria Bridge gauge was recorded.

3.5.2 Morphological responses

Wooler Water

As described in section 3.4.2, in the Wooler Water, the 2009 event was preceded by a large flood event in 2008. While the 2009 flood did cause a significant amount of bank retreat, especially downstream of Wooler, the main effect of this flood was to reactivate sources created by the 2008 flood and rework channel deposits. This led to further bank erosion and reworking and further build-up of channel deposits. The Jacobs (2011) study states that differences in the impacts recorded between the 2008 and 2009 floods, which had almost identical peaks, reflect 2 factors:

- the 2008 event that preceded the 2009 flood triggered pronounced channel enlargement, particularly upstream of Wooler (bed lowering where bank erosion is prevented via hard protection, and widening where bank erosion occurred). This flood distorted the channel form artificially in response to the impact of hard protection on passage of a high magnitude flood and creating ‘space’ for the 2009 flood
- the 2008 flood, while having a similar peak flow to the 2009 event, had a considerably longer duration. This will have increased the duration of erosion, sediment transport and deposition, thereby increasing the amount of change

Overall, the study identified the following primary controls on river behaviour:

- flood frequency, magnitude and duration
- the legacy of past gravel extraction (locally)
- the condition of channel engineering structures designed to promote channel stability
- the effects of bank hardening in altering the natural susceptibility of the bed and banks to erosion

Of these, flood frequency and magnitude were identified as the most important control. The sequence of future events is the critical factor influencing the likely nature of further channel change. As the channel had adjusted its form to accommodate 2 large flood events (2008 and 2009), further channel enlargement would only be expected to occur if a flood of comparable or greater magnitude were to occur in the near future. It is also important to note that the extent of channel widening and bed lowering is likely to have been exacerbated by the presence of hard bank protection, which prevented the natural process of bank erosion from occurring.

River Kent

In the Kent catchment, the 2009 flood event saw extensive areas of gravel and fine sediment deposition occur upstream of the weirs located in the Staveley reach of the Kent (Cowan Head, Bowston and Burneside). Downstream of Burneside the channel remained artificially confined by hard bank protection. However, a significant area of deposition began to appear within the channel adjacent to the golf course. The flood event also triggered widespread bank erosion.

Rivers Derwent and Cocker

The 2009 flood in the Rivers Derwent and Cocker generally resulted in a combination of channel erosion (mainly bank erosion) and flood plain sediment deposition (Jacobs, 2010). However, the severity of these impacts varied in response to the influence of site-specific factors including:

- the degree of natural channel confinement by valley sides and terraces, with erosion and deposition occurring where confinement is the greatest
- the degree of artificial confinement by structures such as road and railway embankments, with erosion and deposition occurring where confinement is the greatest
- the planform of the river channel
- the occurrence of artificial, resistant structures, such as bridges, weirs, bank protection and outfalls, which alter flow patterns and velocities
- the occurrence of natural, resistant structures such as trees, bushes and large wood, which alter flow patterns and velocities
- naturally weak or low points in river banks, which, once breached, acted as conduits for flow onto the flood plain and beyond
- breach points/fragile locations in artificial flood embankments which, once breached, acted as conduits for flow onto the flood plain and beyond

Detailed descriptions of the morphological changes are given in the Jacobs (2010) report, and 3 case studies taken from the report are outlined here to illustrate the main examples, influencing factors and flood impacts. One of the most significant channel changes along the Derwent was observed at Lodge Farm. This site is dominated by a new ‘chute’ channel that cuts across the neck of a bend in the river (Figure 3.8). This channel effectively created an island which was formerly the flood plain and is now covered by coarse sediments. The chute channel could be described as a partial avulsion. The pre-existing bend in the river is still occupied by flow, although there has been some deposition of sediment within the channel.

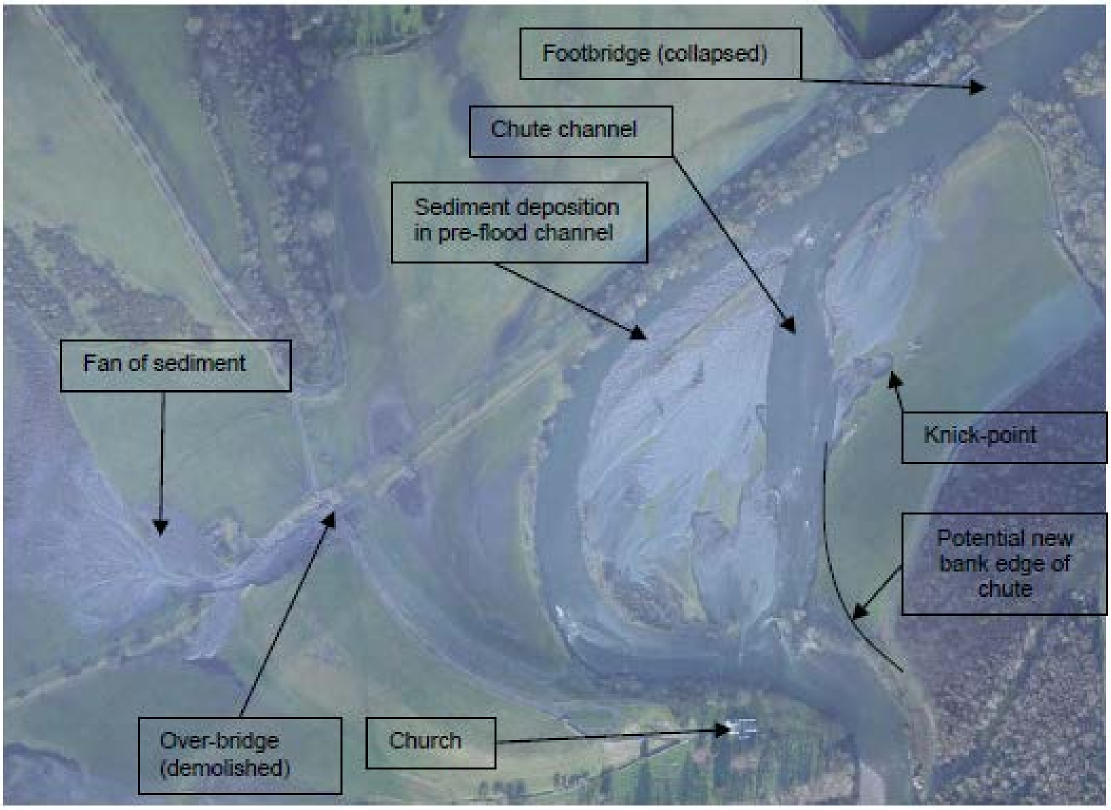


Figure 3-8 Aerial photography of Lodge Farm on the Derwent, from Jacobs (2010)

The study discussed 2 possible theories about the severity of the erosion and deposition at this location. Firstly, it was suggested that the geomorphic change at the site reflected the formation and subsequent collapse of a large wood jam, formed at the upstream end of the site where large wood became trapped on the piers of a footbridge. The collapse of a large wood jam would explain the severity of the damage in this location, including the formation of the chute channel, of which no other examples were observed elsewhere in the catchment. A wave of water surging through the site is also consistent with the damage at an over bridge, which crossed the disused railway line at the downstream end of the site. The disused railway line is raised on an embankment, artificially confining the channel along the right bank. Despite its distance from the river and slightly elevated position above the flood plain, this bridge was partially demolished when a fan of sediment was transported and deposited downstream as the flood water surged over the flood plain.

Secondly, it was suggested that bank protection along the outside of the bend restricted channel change (via bank erosion) during the flood event. Flood flows were therefore concentrated in the areas where extensive geomorphological change occurred. In this case, the channel chute is likely to have occurred as a knickpoint migrated through the flood plain connecting up with the main channel upstream limit. Evidence for this theory is supported by a series of scour patterns in the flood plain that mark locations of other knickpoint migrations. Significant bank erosion has occurred in the location of the church on the right bank, and this appears to be at least partly a result of the formation of the chute channel. Erosion appears to have caused some church graves to fall into the river channel. Downstream of the church, bank erosion has resulted in an access track collapsing.

Severe erosion occurred on the River Derwent in the vicinity of Stainburn Hall Farm, approximately 1 km upstream of the Yearl Weir near Stainburn (Workington). The upstream part of the site is characterised by significant bank erosion along the left bank through a combination of bank retreat and stripping of the top layer of sediments from the flood plain (Figure 3.9). The left bank in this location before the flood event was composed mainly of a degraded agricultural embankment, parts of which may have been lost before the 2009 flood event. This meant the remains of the embankment would therefore have formed the river bank, leaving it vulnerable to erosion.

The report concludes that the bank and flood plain erosion appears to have been caused by flow going out of bank in those locations and being routed across the neck of the large bend in the river. The main line of flow during the peak of the flood is almost perpendicular to the channel where the river crosses the valley floor from the left to the right valley side. The flood flow route could be natural or at least distorted, and possibly caused by human infrastructure.

Figure 3-9 Aerial photograph of the Stainburn Hall Farm site showing breaches in the left bank of the river at the upstream end of the site and coarse sediment splays radiating out from these breaches into the flood plain. Flow is from left to right in the photograph, from Jacobs (2010)

Extensive splays of coarse sediment occurred in the flood plain beyond the bank erosion, reflecting the main route of flow across the neck of the bend in the river at this site. The pattern of these splays reflects differences in the degree of bank erosion, possibly relating to the variations in the condition of the river bank, embankment and degree of vegetation cover before the flood event. The splays of coarse sediment that occurred downstream of reaches in the river bank and embankment are characterised by significant bank retreat. In this context, the embankment breaches are likely to have concentrated flows exiting the channel and either led to, or exacerbated, the crevasse-splay behaviour.

At the downstream end of the site, the left bank has been subject to significant erosion where the flow re-entered the channel (Figure 3.10). Erosion was initiated as flow re-entered the river channel in a relatively concentrated point upstream of a former railway bridge. Flow crossing the flood plain was deflected by the embankment of the former railway line and forced back into the channel. As the flow dropped back into the channel, locally high velocities appear to have been generated, initiating erosion of the river bank and the formation of several knickpoints, which retreated in an up-flow direction into the flood plain.

Figure 3-10 Scars in the flood plain at the downstream end of the Stainburn Hall site, which reflect the up-flow migration of knickpoints, originating at the river bank, during the flood, from Jacobs (2010)

Similar responses were observed in the River Cocker catchment. Many sites outlined in the report experienced bank erosion, resulting in channel enlargement and occasional breaches of embankments. Bank erosion also caused localised channel aggradation via the deposition of a significant amount of gravel within the channel. At a site near Brook Farm in the vicinity of Thackthwaite, overtopping of the embankment occurred along the left bank at the upstream end of the site (Figure 3.11). The River Cocker in this location is modified, with extensive, historic straightening and realignment. The main morphological change at the site was channel widening through bank erosion (Figure 3.12). Extensive erosion occurred along the left bank, which resulted in the partial collapse of a stretch of embankment along the left bank. At the downstream end of the site, a total breach of the embankment along the left bank caused flood plain inundation. In Figure 3.12, the channel, which can be seen joining the main channel on the right side of the river, is the downstream end of a palaeochannel that now conveys flows from several minor tributaries.

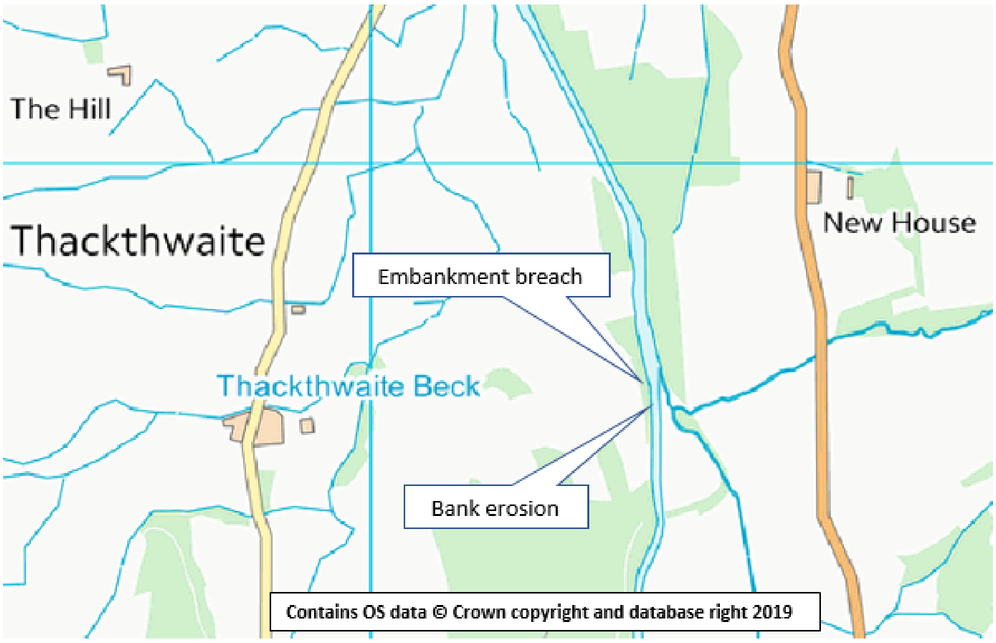


Figure 3-11 Flood impacts at Brook Farm, near Thackthwaite, modified from Jacobs (2010)

Figure 3-12 View looking upstream at the upper end of the Brook Farm site. Erosion is visible along the left and right banks, from Jacobs (2010) 2015 to 2016 flood event

3.6 2015 to 2016 flood event

3.6.1 Background

The extent and duration of flooding during winter 2015 to 2016 ranks alongside the 1975 to 1976 drought and 1947 floods as one of the most extreme, widescale events captured in observational records during the last 100 years at least (Marsh and others, 2016). Exceptional rainfall during the first half of December rapidly eliminated soil moisture deficits and soils remained close to saturation throughout the winter across most of the flood-affected regions. Much of northern UK received double the average December rainfall, with upland areas in the Lake District, north Pennines and the Cairngorms receiving triple the average monthly rainfall (Centre for Ecology and Hydrology, ‘Briefing Note’).

Nationally, previous maximum daily and monthly discharges were exceeded, and 4 relatively discrete episodes of extreme run-off can be recognised. The 4 named storms with the greatest hydrological impacts are listed in Table 3.1. It should be noted that forecast windspeed is the main criterion for designating named storms. Some major flood events, particularly those around 26 December 2015, followed unnamed storms.

Table 3.1 Named storms in the winter of 2015 to 2016 with hydrological impacts

Name	Date of impacts (UK/Ireland)
Abigail	12 to 13 November 2015
Desmond	5 to 6 December 2015
Frank	29 to 30 December 2015
Gertrude	29 January 2016

The record rainfall from Storm Desmond generated exceptional peak flows for many rivers draining upland areas of northern England, while exceptional flows were also widespread during flooding on 26 December, with many major rivers registering new maximum flows. The National River Flow Archive estimated a return period of >200 years for the River Wharfe at Flint Mill Weir, upstream of Tadcaster (Marsh and others, 2016, Table 5). In the Kent catchment, flows in the River Kent and River Sprint on 5 December 2015 were the highest ever recorded.

3.6.2 Morphological responses

River Greta

The River Greta, located in the catchment of the River Derwent in northern Cumbria (Figure 3.13), experienced significant morphological change during Storm Desmond in December 2015 (Wishart, 2018). Subsequent high flows also led to geomorphological change, although this was generally restricted to reactivation and change in features created during Storm Desmond. A particularly detailed analysis of morphological change in the area around Low Briery during the flood event was documented by Wishart (2018). The report examines change in 5 reaches around Low Briery, as outlined in Figure 3.14, a summary of reaches 2 to 5 is outlined below.

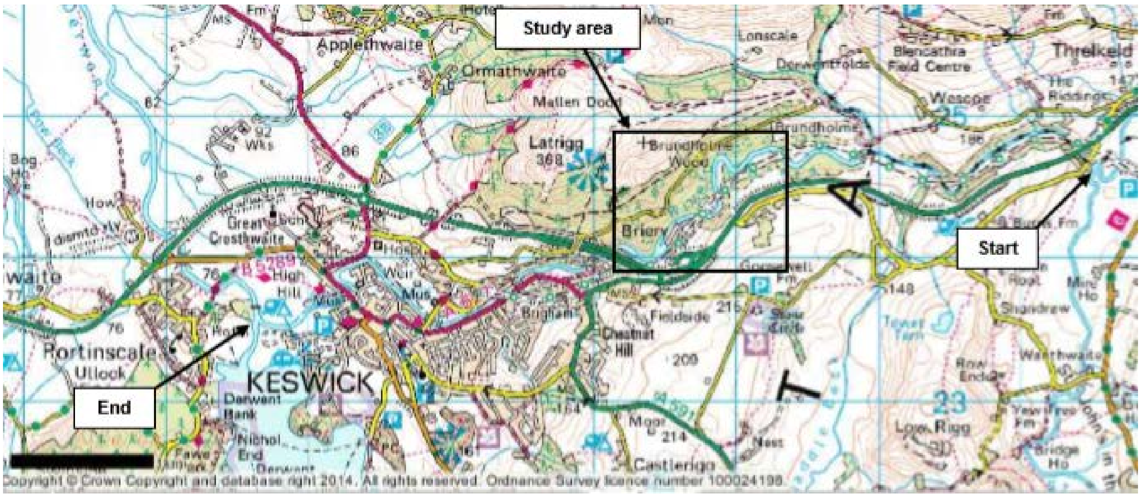


Figure 3-13 Location of the River Greta, from Wishart (2018)

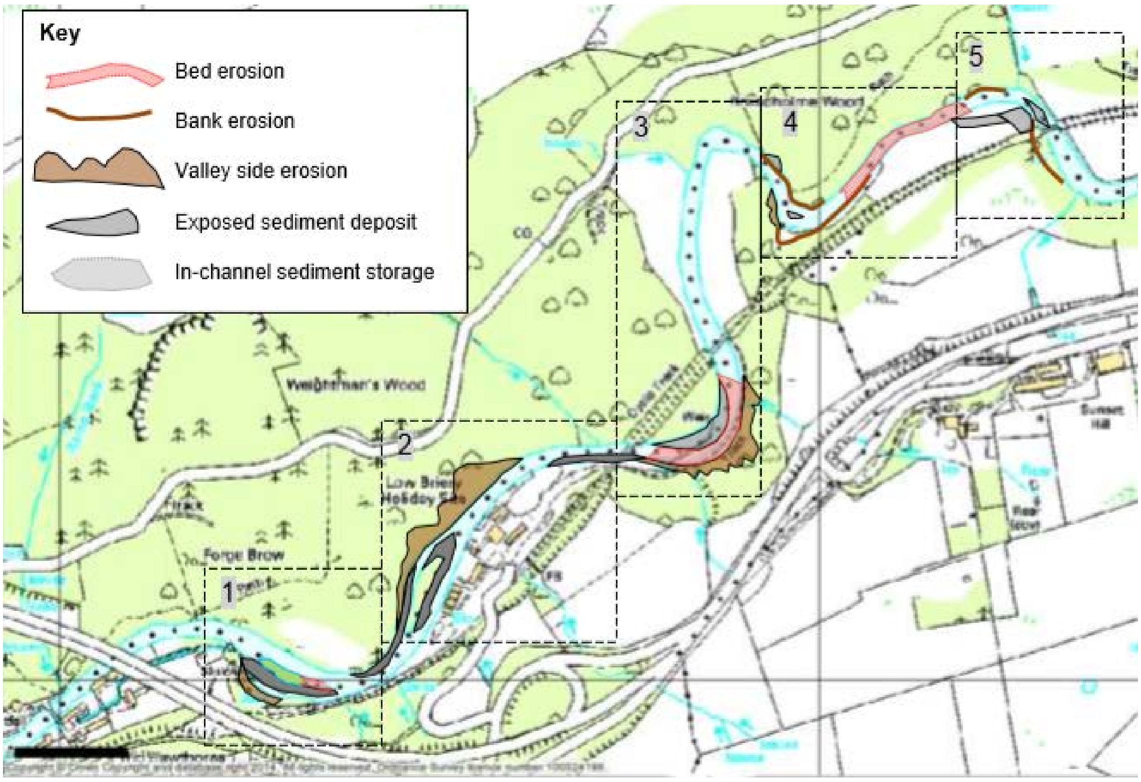


Figure 3-14 Overview map of the main geomorphological impacts in the Low Briery area, from Wishart (2018)

Significant erosion of the valley side occurred in the vicinity of the Low Briery Caravan Park and gauging station, where the river flows around a large island (Reach 2 in Figure 3.14). The valley side erosion involved a combination of erosion of the surface soil and the thin veneer of colluvium (loose sediment), as well as erosion of the underlying weathered bedrock (slates) (Figure 3.15). The island was subject to erosion during the peak of the flood, followed by deposition of coarse sediment in the channel as the flood water receded and flow energy decreased. Woody material, typically whole trees, was also deposited in this section of channel. The study indicated that potential differences in the sedimentological/geological composition and structure of the valley side, along the right side of the river channel, could affect future rates of sediment supply and erosion (although further assessment is needed).

A key control on the occurrence and scale of valley side erosion was the degree of artificial flow confinement. The pronounced valley side erosion observed along the right channel bank is likely to have been exacerbated by confinement of flood flows by walls and other structures, together with some flood plain raising associated with the caravan park and the previous industrial use of the site for milling. In addition, the deflection and confinement of flow by dense in-channel vegetation associated with the island in the river is also likely to have increased the pressure on the right bank.

Wishart (2018) also suggests that the severity of erosion along the right bank in this reach may also reflect the supply of sediment from upstream. A large valley side failure occurred immediately upstream of this reach. This failure is likely to have occurred rapidly, as it was associated with the collapse of the weir, and would have led to a sudden increase in the volume of the flood flow due to the rapid addition of a massive amount of sediment, debris and water.

Figure 3-15 Valley side erosion on the right bank, adjacent to the 'Greta at Low Briery' gauging station, from Wishart (2018)

Further upstream (Reach 3 in Figure 3.14), the river was dominated by extensive erosion of the right side of the valley, around the outside of a larger meander in the river. This valley side erosion was associated with pronounced changes of the river channel due to erosion. Before the flood, the river channel was characterised by a locally steep section of river bed (a cascade), which included the remains of a derelict weir along the crest of the feature (Figure 3.16).

Figure 3-16 Views of the weir site taken (a) before the flood in 2014 (18-02-2014) and (b) following the flood in 2016 (24-03-2016), from Wishart (2018)

The cascade and derelict weir were totally removed by the flood in 2016, and the river bend migrated downstream via erosion of the left bank (Figure 3.16b). It is likely that the downstream shift in the bend in the river was promoted by the presence of the weir-cascade feature. This feature, which formerly ran across the bend in the river, would have focused flows towards the outer bank at the downstream end of the bend in the river.

Retreat of the left bank resulted in pronounced widening of the channel. The high sediment load carried by the flood waters, together with the widening, resulted in the accumulation of a substantial volume of coarse sediment on the inside of the bed of the river in a point bar feature. This feature is likely to have formed after the erosion of the river bed and valley side as the flood waters receded. Subsequent high flows appear to have trimmed the riverwards face of this deposit, which has a very steep face.

The collapse of the weir and the cascade on which it was sited was accompanied by, and likely caused, significant incision. Lowering of the river bed in this location is likely to be the main cause of the valley side erosion through undermining the toe of the slope. The degree of channel change recorded in the vicinity of the former weir also appears to have been influenced by the historic railway bridge and embankment. The embankments across the narrow flood plain caused the flood flows to be focused under the bridge. This led to a degree of channel widening downstream due to erosion of the bank toe along either side of the river. It will also have concentrated flow velocities within the flood flows into the river channel, which will have become increasingly focused along the left bank, exacerbating the erosion triggered by the collapse of the weir-cascade complex. The scale and nature of the slope erosion in this location is also a function of the geology of the valley side in this location.

Interestingly, upstream of the major slope erosion described above, the river experienced relatively little change during the flood event. Approximately 300 m upstream, the river channel abuts the slope of the right side of the valley. There is no evidence that the flood caused any significant erosion of this slope or the channel in between these 2 locations. This is despite the fact that the upper bend is tighter than that downstream, which would increase the concentration of the main flow path against the toe of the slope compared to that downstream where the failure occurred. This lack of a geomorphological response to the flood flows in this location is therefore likely to reflect the relatively uniform bed profile in this location before the flood. As such, the failure of the cascade and weir is highly likely to be the main cause of the valley side erosion.

In reach 4, further upstream, the river experienced a combination of bed and bank erosion (Figure 3.17). In the upper part of the reach, the river bed was almost entirely removed and the underlying bed rock exposed. This bed erosion has undermined a section of revetment that protects the left bank of the channel. The revetment was noted to be already in a state of disrepair before the flood. The severity of channel erosion in this area appears to have been advanced by modifications to the river and the flood plain when the railway was constructed in the valley bottom during the 19th century. The works included removing a bend in the river, and the revetment running along the bank is assumed to have been constructed as part of this channel alignment. Realigning the river into a new course appears to have involved some excavation into bedrock underlying the valley at the upstream end of the new alignment. There is also an embankment running along the top of the left bank, presumably intended to act together with the bank face revetment to prevent the river reoccupying its former channel. Wishart (2018) states that the channel realignment is likely to have promoted the significant change in this location in 3 ways:

- The straighter, and therefore shorter, channel alignment, resulted in a steeper channel gradient increasing the energy of flood flows.
- The left bank embankment will have concentrated flood flows within the channel, thereby increasing the flow energy during the flood.
- The new channel alignment resulted in a very tight turn in the river where it re-joined the pre-existing alignment, concentrating flows against the left bank, the lower portion of which is bedrock. This bedrock acts as a hard point and prevents the channel from migrating through bank erosion.

Figure 3-17 Photograph illustrating the removal of the river bed in the upper half of reach 4, from Wishart (2018)

At the top of the study extent at reach 5, the river underwent a combination of significant channel erosion in the vicinity of the former railway bridge, and sedimentation on the flood plain immediately downstream. Bank erosion along the left bank of the channel caused the abutment to fail. This coincided with erosion of the surrounding flood plain and excavation of a large section of the railway embankment beyond (Figure 3.18). Sediment deposition on the flood plain immediately downstream of the former railway bridge involved the deposition of a relatively uniform veneer of sediment onto the flood plain close to the left bank downstream of the old railway bridge. Beyond this, sedimentation on the flood plain formed a linear, flow-sculpted ridge (Figure 3.19). The pattern of sediment deposition on the flood plain appears to reflect variation in the distribution of flow velocities and turbulence patterns in the flood plain flows. This is influenced by both small-scale factors, such as the presence of trees and obstructions to flow, and also large-scale factors influencing flow patterns at the valley-scale, including valley width and planform.

Figure 3-18 Photographs illustrating the erosion of the right bank leading to erosion of the flood plain and the removal of a sizeable chunk of the railway embankment, from Wishart (2018)

Figure 3-19 Linear ridge of sediment deposited on the flood plain, from Wishart (2018)

Generally, in the Greta catchment, erosion predominated upstream of Keswick, while sediment deposition dominated the area of Keswick (downstream of the A66). The widespread erosion that occurred meant that flood flows associated with Storm Desmond and subsequent high flows experienced through the winter, conveyed a significant sediment load downstream and into the urbanised reach through Keswick. Consequently, a considerable amount of sediment (>20,000 tonnes) was removed from the river channel in Keswick and temporary reactivation of sediment sources occurred.

The scale of the geomorphological impacts reflects the severity of the storm and the resulting river flows. However, Wishart (2018) highlights that the pattern of geomorphological impacts was variable, reflecting that channel response (through erosion and/or deposition), is governed by a wide range of factors which combine to determine the impact of the flood. The factors highlighted include:

- valley flood geometry – width and curvature
- channel structure and geometry – gradient and width especially
- past modification of the river channel
- infrastructure – presence and failure of
- geological controls – nature and extent of drift and solid geology

River Wear

Storm Desmond (5 to 6 December 2015) was noted to accelerate long-term (>100 years) significant morphological adjustments to the severe constriction of a river channel in the vicinity of Kenneth's footbridge on the River Wear at Frosterley (Wishart, 'Case Study: Geomorphological response to an artificial channel constriction').

The erosion (Figure 3.20 and Figure 3.21) is occurring in response to wider, reach-scale changes in the planform of the river upstream of the bridge and has caused the position of the bank to retreat and the planform of the river to become more sinuous.

This impacted on flow patterns and resulted in flow being directed against the left bank of the bridge.

Changes in the flow path and distribution of erosion are also linked to the patterns and quantities of sediment storage. The large deposits of sediment in the channel, on opposite sides to the lengths of eroding bank, are helping to direct flow against the river bank, therefore reinforcing the severity of the erosion. The river channel changes are therefore creating further change, which reinforces the tendency for bank erosion along alternate sides of the channel. The right bank immediately downstream of the railway bridge was formerly protected by gabion baskets (cage, cylinder or box filled with rocks), but these have failed.

The ultimate trigger for this change in channel behaviour was attributed to the construction of a railway line and associated embankment across the flood plain and channel during the latter part of the 19th century. This severely confined the channel, causing a local increase in flow energy that promoted bed scour and downstream sediment deposition.

Figure 3-20 View of the River Wear upstream from Kenneth’s Bridge, from Wishart (‘Case study: Geomorphological response to an artificial channel constriction’

Figure 3-21 View of the River Wear downstream from Kenneth's Bridge, from Wishart ('Case study: Geomorphological response to an artificial channel constriction')

River Kent

Reporting of morphological change in the River Kent catchment is relatively limited, although some information is provided in the post-event flood reports for Storm Desmond prepared by Cumbria County Council, as summarised below.

The Staveley and Ings flood report (Cumbria County Council, 2016c) from this event reported that river scour and sediment movement caused significant problems. River bank erosion was experienced at 1 Rock Cottage, where a riverside retaining wall collapsed due to undermining, also affecting a pedestrian access bridge. There was also erosion damage on the left bank of the River Gowan at Gowan Close, located opposite 1 Rock Cottage. Significant redistribution of sediment also occurred on the River Gowan, notably causing a gravel bank immediately upstream of Abbey Bridge. A riverside retaining wall collapsed as a result of undermining on the left bank of the River Gowan immediately downstream of Abbey Bridge.

The Kendal Flood Investigation carried out following Storm Desmond (Cumbria County Council, 2016b) reports that the water level in the River Kent reached the deck level of the pedestrian suspension bridge (Dockray Hall Footbridge) and severely undermined the foundation of the right pier. Rock armour protection to the river edge was also washed away. The report also outlines that substantial damage was reported on the left bank of the River Kent adjacent to the Carus Green golf course. Previous geomorphology reports produced by the Environment Agency have noted that bank erosion is an ongoing issue in this location. For example, a Geomorphological Site Investigation Report (Brown, 2006) highlighted that the left bank and a short section of the right bank at the golf course are eroding. This is occurring as the river attempts to actively meander across the flood plain. The report concluded that maintenance of the golf course land to the bank edge was not helping the situation and asserted that allowing a wild scrub area to develop would mean root matrix and vegetation could provide bank protection. A variety of bank protection was installed on the left bank, ranging from blockstone to turfed timber-toe and rock armour backfill (date of installation unknown). The presence of this protection, however, restricted the lateral erosion of the left bank and this, together with the formation of a large mid-channel gravel shoal, meant that erosion was concentrated on the unprotected right bank (Brown, 2008). The Geomorphology Site Investigation report (Brown, 2008) highlighted that the bank protection has failed in places.

Figure 3-22 Section of erosion on left bank of the River Kent, adjacent to Carus Green Gold course, from Cumbria County Council (2016c)

The fluvial audit of the River Kent carried out by JBA Consulting reported geomorphological changes following the 2015 flood (JBA Consulting, 2018). The report stated that after the 2015 flooding, many dormant sediment sources were reactivated and new sources were created. The sources included river bank erosion, eroding valley sides and unstable mine workings, for example around the area of Longsleddale Church. The report highlighted that in the 2015 floods, gravel extraction occurred and was placed on the flood plain as embankments of piles of sediment. The sediment from these sources and those that were transferred downstream represented a significant and ongoing risk of flooding in downstream communities in and around Kendal, where the accumulation of sediment was seen to reduce channel capacity. The fluvial audit indicated that the River Kent through Kendal acts as a sink for sediment transferred down from its upper reaches, as well as from other tributaries, as a result of steep gradients and strong connectivity with surrounding hillslopes. The fluvial audit reports that landslides occurred following the 2015 floods, inputting large amounts of sediment into the Kent river system.

River Wharfe

On 26 December 2015, flooding associated with heavy rainfall following Storm Eva occurred, particularly affecting the Lower Wharfe. Tadcaster, situated in the lower Wharfe catchment in Yorkshire, was severely affected by the flooding. On 29 December 2015, high flows in the Wharfe caused the 18th century Tadcaster Bridge to collapse. The bridge was originally constructed with 9 arches. The river channel under the bridge has narrowed over many years due to natural deposition and the reclamation of land, and only 7 arches remain visible. At the time of the flood, 3 arches were fully blocked, 3 were partially blocked, and 3 remained fully open and allowed the river to flow freely during normal conditions (Historic England, 2016), cited in North Yorkshire County Council (2017). There were public concerns that the full and partial blocking of 6 of the 9 arches of the bridge in the preceding years contributed to the extent/depth of flooding. However, a hydraulic modelling study (JBA Consulting, 2016) demonstrated that high water levels downstream rather than the bridge were the main control on water levels upstream (North Yorkshire County Council, 2017).

3.7 Summary

This section has examined 5 flood events, the morphological responses reported in the river channels as a result of those flood events as well as the reported causes. A summary of the geomorphological impacts, causes/influencing factors, and flood impacts for each flood event is presented in Table 3.2. The influencing/main factors are colour-coded according to whether they are natural (blue) or man-made (grey). The morphological responses observed and influencing factors reported reflect the upland nature of these rivers. The case studies are located in process domains 2 and 3 and are not representative of lower energy situations (process domain 4).

Table 3.2 Morphological responses and main exacerbating factors from the flood data review. Natural and man-made factors are colour-coded blue and grey, respectively

Flood event	Catchment	Morphological responses/ styles of adjustment	Related flood impacts	Influencing/main factors (reported or assumed)
2005	River Caldew	Erosion on outside of meanders, deposition on inside of meanders, causing flow deflection and reinforcing potential for erosion	Loss of land at channel margins	Sediment supply and connectivity
	River Caldew	Channel widening and sediment deposition upstream on straighter sections	Loss of land at channel margins	Sediment supply and connectivity Large wood and riparian vegetation (tree collapse - either during or before the event)
	River Caldew	Reorganisation of sediments at weirs. Deposition upstream causing bank retreat, and cut through of sediments downstream due to channel migration		In-channel structures (weir)
	River Caldew	Increase in extent of active channel deposits (both from reworking of old		Sequencing of flood events

Flood event	Catchment	Morphological responses/ styles of adjustment	Related flood impacts	Influencing/main factors (reported or assumed)
		surfaces and the formation of new deposits from upstream)		Sediment supply and connectivity
	River Kent	Overtopping of banks and new flow routes across the flood plain	Flooding of properties in vicinity of bridge	Large wood and riparian vegetation (recruitment of large wood via bank erosion) In-channel structures (blockage of bridge with large wood)
2007	River Wharfe	Overtopping of banks and new flow routes across the flood plain		In-channel structures (blockage of culvert with large wood)
2008	River Till	Flood bank failure/breaching, triggering crevasse-splay deposition and flood plain scour		Flood plain infrastructure (embankment artificially confining channel) Channel modification (past realignment) Asset failure (embankment breach) Sinuosity (failure often occurred at the apex of abrupt river bends)
	River Breamish	Bank erosion	Undermining of road, ford, footbridge and electricity pylon	Flood plain infrastructure (resulting in artificial confinement), In-channel structures (ford), Bank material (thick sequences of 19th and 20th century alluvial sand and gravel)
	River Breamish	Breach of embankment, triggering crevasse-splay deposition and flood plain scour		Flood plain infrastructure (embankment artificially confining channel) Channel modification (past realignment) Asset failure (breach of embankment)
	River Glen	Avulsion, reactivation of palaeochannels, triggering crevasse-splay deposition and flood plain scour		Flood plain infrastructure (embankment artificially confining channel) Channel modification (past realignment) Asset failure (embankment breach)
2009	Wooler Water	Bank retreat and erosion, reactivation of sediment sources created by previous (2008) flood and reworking of channel deposits		Magnitude, duration and sequencing of flood events In-channel structures (bank protection) Channel maintenance/dredging (legacy of past gravel extraction) Asset failure (condition/failure of channel engineering structures/bank protection)
	River Kent	Extensive areas of sediment deposition upstream of weirs		In-channel structures (weirs)

Flood event	Catchment	Morphological responses/ styles of adjustment	Related flood impacts	Influencing/main factors (reported or assumed)
	River Derwent	Chute channel creation, which could be described as a partial avulsion, coupled with coarse sediment deposition		UNCERTAIN, BUT POTENTIALLY: Large wood and riparian vegetation Flood plain infrastructure (raised railway embankment) In-channel structures (collapse of large wood jam, formed from large wood trapped at footbridge structure) OR Flood plain infrastructure (raised railway embankment) In-channel structures (constriction of flows by hard bank protection causing knickpoint migration).
	River Derwent	Breach of embankment, triggering crevasse-splay deposition and flood plain scour		Flood plain infrastructure (degraded agricultural embankment) Asset failure (degraded agricultural embankment)
		Bank erosion, where flow across the flood plain re-entered the river		Flood plain infrastructure (embankment of former railway bridge artificially confining channel)
	River Cocker	Bank erosion resulting in channel enlargement and localised aggradation, triggering of breaches in the embankment in places		Flood plain infrastructure (embankment) Channel modification (past realignment) Asset failure (embankment breaching)
2015	River Greta	Valley side erosion through fluvial toe-scour and slope processes		Sediment supply and connectivity (valley side failure upstream leading to sudden increase in flood flow due to inputting large volumes of sediment debris and water) Large wood and riparian vegetation (Vegetation on island deflecting and confining flows) Flood plain infrastructure (structures and flood plain raising)
	River Greta	Bed incision and associated valley side erosion		Flood plain infrastructure (historic railway bridge and embankment confining channel) In-channel structures (derelict weir focusing flows onto valley side) Asset failure (failure of derelict weir) Geology

Flood event	Catchment	Morphological responses/ styles of adjustment	Related flood impacts	Influencing/main factors (reported or assumed)
	River Greta	Bed incision and bank erosion		Flood plain infrastructure (embankment) Channel modification (re-alignment) In-channel structures (bank revetment) Asset failure (undermining of bank revetment, poor state of disrepair before flood event)
	River Greta	Bank and flood plain erosion		Flood plain infrastructure (railway embankment) In-channel structures (bridge)
	River Greta	Significant sediment deposition in Keswick	Ongoing risk of flooding in Keswick due to decrease in channel capacity	Magnitude, duration and sequencing of flood events (2015 Storm Desmond and subsequent high flows throughout winter) Sediment supply and connectivity Flood plain infrastructure (flood walls in Keswick, artificially confining channel) Land use changes (urbanisation)
	River Wear	Acceleration of pre-existing, significant erosion in the vicinity of infrastructure		Flood plain Infrastructure (railway line across flood plain and channel, artificially confining flow) In-channel structures (bridge, gabion protection) Asset failure (failure of gabion bank protection)
	River Kent	Bank erosion and scour		In-channel structures (retaining walls, bridges, rock armour protection)
	River Kent	Bank erosion	Loss of golf course land	Channel maintenance (riparian vegetation maintenance) In-channel structures (bank protection preventing natural adjustment Asset failure (bank protection)
	River Kent	Activation of dormant sediment sources and creation of new sources, as a result of bank erosion, eroding valley sides, landslides and unstable mine workings	Ongoing risk of flooding in downstream communities such as Kendal as a result of sediment from these sources being transported downstream	Sediment supply and connectivity Flood plain infrastructure (unstable mine workings, embankments of piles of sediments)

4 Main factors that could influence the scale of sensitivity to morphological change during flood events

4.1 Main influencing factors

Eleven main influencing factors have been identified and have been selected as the most important in terms of their potential to influence channel sensitivity to morphological change. Based on this background research (Table 2.4 & Table 3.2), the main factors affecting morphological response to flooding are summarised as:

- bedrock/valley confinement
- channel slope (natural)
- magnitude, duration and sequencing of flows
- sediment supply and connectivity
- large wood and riparian vegetation
- flood plain infrastructure, including:
    - flood related infrastructure (embankments, land raising for flood management, flood walls)
    - other flood plain infrastructure (transport infrastructure, buildings, pylons, services)
- channel modification, including historic works that have altered channel dimensions and planform, including:
    - channelisation/straightening
    - planform (realignment)
- channel maintenance, including:
    - works to remove accumulated sediments (fine sediments as well as coarser cobble/gravel sized material)
    - vegetation management and removal
- in-channel structures, including:
    - bounding structures on one boundary of the channel only, such as bank or bed protection, which prevent lateral migration or bedform creation and which may become undermined/outflanked especially in major floods
    - bounding structures on both sides of the channel such as culverts, parallel bank protection or bridge abutments, which may constrict flow leading to increases in velocity

    - structures that partly block the channel or affect part of the cross section form, such as outfalls, piers, groynes, partly-broken weirs, which tend to cause scour
    - channel-spanning structures such as trash screens or weirs that pond and cause aggradation upstream and may lead to sediment starvation
- asset failure, including:
    - breaching/overtopping of flood defences
    - outflanking of hard bank protection
    - failure of hard bank protection
    - partial or full collapse of in-channel structures such as weirs or bridges
- land use changes, including:
    - urbanisation
    - deforesting for agriculture
    - forest management
    - removing vegetation

4.1.1 Ranking factors

The influencing factors operate at different time and space scales. Some, such as bedrock valley confinement are relatively static factors, while others such as channel maintenance and dredging are human activity factors. The majority are conditions/states before flood events but some, such as asset failure, occur during a flood event. As such, it is very difficult to rank the factors in order of how influential they are.

Certainly, based on the literature and flood data review, human factors are generally more influential than natural factors because they are so effective in constraining the inner band of the river evolution diagram proposed by Brierly and Fryirs (2016) (Figure 2.2, Figure 2.3), turning reversible river behaviours into irreversible river changes. It would appear that significant morphological changes are often: related to the presence of flood plain infrastructure and in-channel structures; locations where channel modification has occurred, particularly past realignment, and in systems with active sediments.

While the impacts of human modification on a fluvial system are highly site specific, and partly depend on the balance of pre-existing natural factors, they are also so widespread as to be considered pervasive. For example, removing relatively static large wood from a small, upland channel, may have a much greater impact on channel morphological response than removing relatively mobile large wood from a large, lowland channel. This issue of site specificity highlights the difficulty of extracting a small number of key factors that are most important in determining morphological sensitivity, as most of the factors on the list cannot be viewed in isolation and are more important in some locations than others. That said, it can be concluded that the unintended consequences or failure of human features and infrastructure commonly exacerbates channel changes in reaches that are naturally sensitive, and may trigger changes in reaches naturally insensitive to morphological response.

Based on the insight gained form the literature and flood report review, the main factors (based on the occurrence of the factors in Table 2.4 & Table 3.2) can be summarised as follows:

Dominant factor:

Channel confinement

- Bedrock/valley confinement
- Human confinement
    - Flood plain infrastructure
    - in-channel structures
    - asset failure
    - channel modification

Other factors:

Sediment supply and connectivity

Large wood and riparian vegetation

Magnitude, duration and sequencing of flows

Channel maintenance

Land use changes

Channel slope (natural)

The dominant influencing factor of channel confinement is associated with natural confinement as well as past and current human interventions in the channel. In fact, nearly all of the examples cited in the review of flood-generated adjustments involve past or current human factors. These human influences have been shown to be very effective in constricting the river's capacity to adjust. Their effect is to turn responses that would have been reversible, and within the natural capacity for adjustment, into irreversible changes. These human factors trigger, amplify and distort morphological responses to flood events. It is essential to recognise that, in many cases, the combined effects of particular groups of factors are far more effective in generating channel changes than the sum of their parts, leading to heightened sensitivity.

4.2 How rivers adapt to confinement

The majority of UK rivers are confined or partially confined by natural or human controls in their alluvial reaches. According to Hey (1978), natural, alluvial, unconfined channels possess 9 modes of self-adjustment (or degrees of freedom) because they have the ability to adjust their cross-sectional shape (3 variables), slope (one variable), plan shape (2 variables), velocity (one variable) and bed forms (2 variables) in response to erosion and deposition. Hey's modes of self-adjustment are used in this section as a framework for examining how influencing factors affect the morphological response of river channels during flood events.

Each mode of self-adjustment has a governing or controlling equation associated with it that not only defines the connections between the dependent variables, but also how the channel responds to a set of controlling (independent) variables in the adjustment process. These equations, therefore, define the processes of channel adjustment to a set of external constraints, which are responsible for the hydraulic geometry of alluvial channels. The controlling (independent) variables identified by Hey (1978) are discharge, input sediment load, bed and bank material size and valley slope. The modes of self-adjustment and controlling variables identified by Hey (1978) are outlined in Table 4.1 and Table 4.2 respectively. Note that Hey originally expressed the cross-sectional shape in terms of bankfull wetted perimeter, bankfull hydraulic radius and maximum bankfull flow depth. However, considering that in wide rectangular channels hydraulic radius is approximated by the flow depth, it can be assumed that for UK river systems, the maximum bankfull flow depth and width are adequate to represent cross-sectional shape.

Although Hey's modes of self-adjustment were originally developed for alluvial, unconfined systems, they still provide a useful framework for investigating how local, confining factors distort or amplify a river's morphological response during a flood event. A river only possesses the full 9 degrees of freedom in alluvial reaches, with the degrees of freedom reducing as the channel becomes less alluvial. It is this reduction in the degrees of freedom that exacerbates and/or distorts channel response (C. Thorne, pers. Comm.). Removing a degree of freedom concentrates the response of a river in the other, remaining degrees of freedom. For example, a concrete invert in the channel bed removes the potential for adjustments to the bed elevation and local channel slope, effectively precluding depth and valley slope responses and potentially driving different responses and/or amplifying responses in the remaining degrees of freedom.

Table 4.1 Modes of self-adjustment of a river channel (dependent variables)

Dependent variables (type)	Dependent variables (measurement)
Cross-sectional shape	Maximum bankfull flow width (w_m)
	Maximum bankfull flow depth (d_m)
Slope	Channel slope (S)
Plan shape	Channel sinuosity (p)
	Meander arc length (z)
Velocity	Average bankfull velocity (V)
Bed forms	Bankfull dune wavelength (λ)
	Bankfull dune height (Δ)

Table 4.2 Controlling variables (independent variables)

Dependent variables (type)	Dependent variables (measurement)
Discharge	Discharge (Q)
Input sediment load	Sediment discharge (input)
Bed and bank sediment size	Bed sediment diameter (D_b)
	Standard deviation of bed sediment (σ_b)
	Right bank sediment diameter (D_r)
	Standard deviation of right bank sediment (σ_r)
	Left bank sediment diameter (D_l)
	Standard deviation of left bank sediment (σ_l)
Valley slope	Valley slope (S_v)

4.2.1 Combining distorted/amplified modes of self-adjustment with main influencing factors

A detailed analysis of the potential impacts of the influencing factors on the morphological response of a river during a flood is presented in Appendix A. This has been carried out by considering how the influencing factor can directly and/or indirectly influence the modes of adjustment and controlling variables outlined in Hey's 1978 paper. A summary of this analysis is presented in Table 4.3 below.

Pre-existing, ongoing and progressive processes of adjustment such as incision and aggradation may arise from influencing factors (for example, land use change, reservoir construction and other human activities), as described in Table 4.3, as well as from broader catchment-wide factors. These can, in turn, exacerbate the impact of floods. These impacts are much harder to predict (as they can arise from both local and catchment factors) and are not considered as an individual, influencing factor due to the complexity of this response.

Table 4.3 Impact of influencing factors on the flood response of a watercourse

Influencing factor	Are Hey's variables (dependent or independent) impacted by the local factor?	
Bedrock/valley confinement Channel confinement can occur in steep and resistant valley margins, which reduces the potential for lateral migration and flood plain dissipation. High velocity flows are therefore concentrated through an unusually small flow area. Water may pool upstream of confined areas, with the confined section acting as a 'hydraulic jet' and vast sediment deposition occurring downstream of the constriction where velocities suddenly decreased. The input sediment load could potentially be impacted by confinement if sequencing is taken into account (downstream of constriction).	Cross-sectional shape	YES
	Slope	YES
	Plan shape	YES
	Velocity	NO
	Bed forms	NO
	Discharge	NO
	Input sediment load	YES
	Bed and bank sediment size	NO
	Valley slope	NO
Channel slope (natural) Channel forms and processes are sensitive to slope. The potential response to flood events is more severe in upland /steep reaches compared to lowland/low gradient systems. However, this is often offset by other factors such as available sediment supply and the erodibility of the bed and banks.	Cross-sectional shape	YES
	Slope	YES
	Plan shape	YES
	Velocity	YES
	Bed forms	YES
	Discharge	NO
	Input sediment load	NO
	Bed and bank sediment size	YES
	Valley slope	NO
Magnitude, duration and sequencing of flows All aspects of the flow regime have an impact on river morphology, including flow frequency, sequencing, magnitude and duration (Soar and Thorne, 2001). In the frame of geological setting, the discharge generated during a flood event determines the capacity of the river to perform geomorphic work (Bizzi and Lerner, 2015). Flood effectiveness is determined by the discharge, sequence and magnitude driven by climate change and landscape topography, translated into geomorphic work by confinement, slope and grain size.	Cross-sectional shape	YES
	Slope	YES
	Plan shape	YES
	Velocity	YES
	Bedforms	YES
	Discharge	YES
	Input sediment load	YES
	Bed and bank sediment size	YES
	Valley slope	NO
Sediment supply and connectivity	Cross-sectional shape	YES
	Slope	YES

Influencing factor	Are Hey's variables (dependent or independent) impacted by the local factor?	
Flooding may often activate a variety of sediment sources, through river bank erosion, eroding valley sides, unstable mine workings and landslides. In some cases, flooding will only cause a long-term change in the channel planform if coupled with the influx of sediments from reactivated sediment sources. Reactivated sediments are deposited downstream of the source, causing morphological change. Major geomorphic change may be concentrated at tributaries, where the sediment supply is increased.	Plan shape	YES
	Velocity	YES
	Bedforms	YES
	Discharge	NO
	Input sediment load	YES
	Bed and bank sediment size	YES
	Valley slope	NO
Large wood and riparian vegetation In-channel woody material alters the cross-sectional flow area of the channel, causing locally significant increases in shear stress and erosion/scour during flood events (in narrowed sections), as well as local flow impoundment and sediment aggradation upstream. In-channel woody material has the potential to trigger changes in channel planform by deflecting flows to opposite banks, increasing erosion and encouraging increased channel sinuosity. Failure of riparian trees caused by bank erosion can lead to widened cross sections. Changes to riparian vegetation can impact on the transmission of flood waters to reaches further downstream.	Cross-sectional shape	YES
	Slope	NO
	Plan shape	YES
	Velocity	YES
	Bed forms	YES
	Discharge	NO
	Input sediment load	NO
	Bed and bank sediment size	NO
	Valley slope	NO
Flood plain infrastructure Infrastructure on flood plains can restrict and confine morphological adjustment of rivers during flood events. High velocity flows are therefore concentrated through an unusually small flow area. This may cause channel widening/bank erosion in these confined areas, which can undermine structures. Sediment deposition may occur downstream of constrictions where flow velocities are reduced.	Cross-sectional shape	YES
	Slope	NO
	Plan shape	YES
	Velocity	YES
	Bed forms	YES
	Discharge	NO
	Input sediment load	NO
	Bed and bank sediment size	YES
	Valley slope	NO
Channel modification (channelisation/straightening, restoration, realignment) Channelisation may involve alteration of the cross section, such as narrowing, widening or deepening. These alterations may cause channel degradation upstream of the modified reach, which is exacerbated during flood events. This is where channel bed incision and bank undercutting occur, which steepen the banks and make them prone to bank failure, further widening the channel. Eroded sediments may be deposited in downstream reaches. Morphological adjustment of a channel reach may be extremely limited by realignment as part of channelisation. In these situations, floodwaters are quickly conveyed downstream, therefore, the channel response to floods may be more visible downstream. As with channel width changes, channel degradation upstream of the modified reach may be accentuated during flood events and sediment deposition may occur downstream. If deposited sediment forms a plug, channel avulsion may occur as the channel attempts to morphologically adjust back to its natural state. Water that spills onto the flood plain may flow in palaeochannels.	Cross-sectional shape	YES
	Slope	YES
	Plan shape	YES
	Velocity	YES
	Bed forms	YES
	Discharge	NO
	Input sediment load	NO
	Bed and bank sediment size	YES
	Valley slope	NO
	Cross-sectional shape	YES

Influencing factor	**Are Hey's variables (dependent or independent) impacted by the local factor?**	
Channel maintenance Occurrence and frequency of in-channel vegetation clearance and/or sediment removal will alter channel capacity and substantially impact the potential morphological change caused by a flood event.	Slope	YES
	Plan shape	NO
	Velocity	YES
	Bed forms	YES
	Discharge	NO
	Input sediment load	NO
	Bed and bank sediment size	YES
	Valley slope	NO
In-channel structures In-channel structures such as weirs, culverts and bridges may cause impoundment and sediment aggradation upstream. Scour may occur downstream and around the abutments of bridges. Large wood may have a similar effect when blocking the channel. In-channel structures such as culverts and trash screens may get blocked by debris. This may cause water levels to back up and the main channel to divert its course.	Cross-sectional shape	YES
	Slope	YES
	Plan shape	YES
	Velocity	YES
	Bed forms	YES
	Discharge	NO
	Input sediment load	NO
	Bed and bank sediment size	YES
	Valley slope	NO
Asset failure During flood events, flood defences may be overtopped, which can trigger bank failure and breaching in some locations, leading to flood plain scour and redeposition of sediment on the flood plain. Where confined by flood defences, high velocity flows may result in channel adjustment during flood events (bank erosion). This may cause damage and/or failure of the defences. Weir collapse during a flood event will increase channel slope and sediment load, as well as altering the channel cross sectional shape.	Cross-sectional shape	YES
	Slope	YES
	Plan shape	YES
	Velocity	YES
	Bed forms	YES
	Discharge	NO
	Input sediment load	YES
	Bed and bank sediment size	YES
	Valley slope	NO
Land use changes Widespread land use change may cause increased channel sensitivity throughout a large portion of the catchment. Land use change can affect run-off and sediment supply and therefore event characteristics within a catchment and delivery to a reach/site. For example, land use changes that decrease infiltration rates and increase flood plain erosion, such as deforesting for agriculture, may increase the sediment load and deposition in the channel. Urbanisation may increase surface run-off and discharge in the channel, which can cause high rates of downstream bank erosion as the channel adjusts to accommodate higher flows. These effects are usually more localised.	Cross-sectional shape	NO
	Slope	NO
	Plan shape	NO
	Velocity	NO
	Bed forms	NO
	Discharge	YES
	Input sediment load	YES
	Bed and bank sediment size	YES
	Valley slope	NO

4.3 Using data to identify influencing factors

There are a variety of data sets available that can be used to identify where influencing factors may lead to hotspots of potential change. The potential for using data sets (particularly GIS data sets) to identify hotspots of potential channel change is presented in Table 4.4. The literature and flood data reviews have shown that often the influencing factors are more important in combination. Consequently, the links between factors are also explored in Table 4.4. However, the potential linkages between factors are numerous, and therefore not all of these have been captured in the table below.

One factor, the magnitude, sequencing and duration of flows, has been excluded from Table 4.4 as it is not readily represented by national, spatial GIS data sets and therefore it would be difficult to use flow data sets to identify hotspots of change.

Table 4.4 Data sets to identify influencing factors

Local factor	Data sets	Identifying hotspots of change
Bedrock/ valley confinement	Aerial imagery BGS Drift/solid geology maps Fluvial audit	The presence of bedrock/valley confinement, indicating relatively stable reaches, can be identified from aerial imagery and BGS geology maps.
Channel slope (natural)	LiDAR OS mapping	Channel slope can be identified using LiDAR and OS mapping. This should be checked in combination with BGS drift geology maps and aerial imagery to identify areas that are steep with erodible alluvial deposits and a lack of stabilising riparian vegetation.
Sediment supply and connectivity	Aerial imagery Fluvial audit Pre- and post-flood survey of sediment accumulation	The rate of sediment supply and resulting channel response to flood events could potentially be identified from aerial imagery, although more local data such as a fluvial audit would provide more detailed information. Similarly, local data such as pre- and post-flood surveys of sediment accumulation can identify areas where sediment deposition may alter the channel's sensitivity to flood flows.
Large wood and riparian vegetation	Fluvial audit Aerial imagery	The presence of in-channel large wood could be identified together with (upstream of) small capacity in-channel structures (bridges and culverts) to flag potential hotspots of flow blockage and overbank flows. This would be difficult to achieve using existing GIS data sets. However, any local, detailed data such as a fluvial audit could be used to identify in-channel large wood together with Environment Agency asset data to identify small capacity structures.
Flood plain infrastructure	Environment Agency asset data Fluvial audit OS MasterMap	The presence of flood plain infrastructure in close proximity to river channels (identified using aerial imagery, Environment Agency asset data and OS Mastermap) could be identified in combination with low gradient alluvial reaches (as identified by BGS geology maps, OS mapping and aerial imagery) to flag potential hotspots of channel change.
Channel modification	Historic mapping Aerial imagery LiDAR Integrated hydrological digital terrain model (CEH) Environment Agency records Environment Agency asset data	Channel modification could be identified using historic mapping, aerial imagery, LiDAR and Environment Agency records to flag potential hotspots of channel change, both within modified reaches, but also upstream and downstream. Additionally, the Environment Agency asset data defences layer includes wall defences that could potentially be used to identify channelised reaches.

Local factor	**Data sets**	**Identifying hotspots of change**
Channel maintenance	Environment Agency records Fluvial audit	Identifying reaches in which channel maintenance and dredging (historic or contemporary) could potentially exacerbate channel change would be difficult to achieve using existing GIS data sets. The main source of data would need to be records of maintenance provided by the Environment Agency. Local data, such as a fluvial audit, could also be used to understand potential hotspots of change within the wider river system that are a consequence of the management activities in the catchment.
In-channel structures	Environment Agency asset data Fluvial audit OS MasterMap	The location of in-channel structures can be identified from existing GIS data sets, such as Environment Agency asset data, OS MasterMap and OS mapping.
Asset failure	Fluvial audit Asset inspection records Environment Agency asset data	Interrogating Environment Agency asset data and asset inspection records could identify hotspots of potential change, especially where assets are found to be in a poor state of repair or in combination with historic channel realignment.
Land use changes	OS mapping Aerial imagery CORINE	Aerial imagery and CORINE could be interrogated to identify areas of land use change within catchments (deforestation, urbanisation) that are likely to cause potential hotspots of channel change further downstream in the catchment.

5 Conclusions

5.1 Morphological and sedimentological impacts during flood events

A literature review has been carried out to examine existing evidence of morphological and sedimentological impacts during flood flow conditions, and to investigate what influences the type, scale and extent of morphological response.

Using conceptual models such as the river evolution diagram presented by Brierley and Fryirs (2016) and the stream evolution triangle (Castro and Thorne, 2019), a number of variables have been identified that determine river behaviour, evolution and morphological response to flood flows. River morphology is highly dependent on relatively constant, imposed boundary conditions (for example, lithology, topography, valley width and confinement) and changeable factors and interactions that occur within this imposed context (flux boundary conditions), for example, magnitude, duration and sequencing of flows, sediment supply, biological interactions. Any change in these boundary conditions can cause behavioural and associated changes in river morphology. Geological controls on relief as well as climatic controls on discharge and vegetation dictate the energy and sediment supply within a river, which determines river morphology and type. These boundaries set the range of river types that are likely to occur, as well as their response to disturbance events such as floods.

Based on these natural factors, 4 broad process domains in a fluvial system, from source to mouth, were outlined, in which the response of the system is relatively similar. The typical morphological responses of specific channel types within these domains and their overall general morphological stability are detailed. The review used Church's (2002, 2006) classification of 6 alluvial channel types based on bed mobility, which is measured by the bankfull Shields stress. While this provides a good indication of morphological stability of a channel in relation to flood flows, it is important to note that in many English and Welsh rivers the bankfull capacity is not natural, having been increased for flood control and land drainage purposes.

Lateral and longitudinal connectivity and coupling are key themes that underpin the literature review and are highlighted as important influences on catchment-wide responses to flood events of different frequencies and magnitudes. Human modifications to the channel (for example, in-channel structures, channel realignment) or flood plain (for example, land use changes, flood plain infrastructure) disrupt longitudinal and lateral hydrological and sedimentological connectivity in most English and Welsh rivers. This reduces or expands a system's 'expected capacity of adjustment', triggering a channel to respond to a flood event in a completely different way from what would be anticipated for the channel in its natural state.

The literature review also explored how behavioural changes in a fluvial system may result from a flood event, which expand or contract a system's expected capacity for adjustment. These initial changes may therefore impact the way in which the system responds to a future flood event, by pushing it closer to a threshold. These are natural adjustments that are key to continuing to provide fluvial ecosystem services. However, if a river erodes its banks to shift the channel closer to properties, infrastructure or agricultural land, or conveyance in a river is reduced in these locations, then flood hazard is increased. It is important that this is recognised; estimating flood hazard is often based on the assumption of a stationary channel, which could lead to large inaccuracies when considering flood risk.

5.2 Review of flood events

Five flood events from 2005, 2007, 2008, 2009 and 2015 to 2016 were selected to be considered. The data reviewed included a variety of flood investigation reports and fluvial audits. This data was supplemented by searching online sources such as local newspapers, met office weather data. The background cause of each flood event was examined, as well as the morphological channel change in response to the flood event and any resulting flood impacts. The documents detailed key modes of channel change that occurred. These included (but are not limited to):

- significant bank erosion augmented by large amounts of sediment deposition in-channel, which deflects flows to cause increased erosion of opposite bank, increasing reach sinuosity
- increased deposition extents upstream of structures, triggering/enhancing bank retreat
- increased extent of active deposits in the channel, both through the reworking of active channel deposits and the formation of new deposits from sediment supplied from upstream
- blocking of structures, leading to diversion of flood flows into the flood plain
- overtopping of flood defences, triggering flood bank failure/breaching, scour of the flood plain surface and deposition on the flood plain
- in-channel gravel deposition leading to out-of-bank flow, partial avulsion activation of palaeochannels and flood plain/channel changes
- channel adjustment involving widening and deepening and the creation of large numbers of additional sediment sources and channel deposits
- valley side erosion through fluvial and slope processes
- acceleration of ongoing, significant morphological change, especially in areas of flood plain infrastructure and in-channel structures
- extensive scour caused by turbulence around infrastructure/structures

5.3 Main influencing factors

Channel response, through erosion and/or deposition is governed by a wide range of factors which together determine the impact of a flood event. The literature review and flood data review in the preceding sections have made it possible to identify key factors that could potentially influence the scale of sensitivity to morphological change during flood flow events.

Eleven main influencing factors have been identified and have been selected as the most important in terms of their potential to influence channel sensitivity to morphological change.

Based on the insight gained from the literature and flood report review the dominant factor is channel confinement. Other key influencing factors are: sediment supply and connectivity; large wood and riparian vegetation; magnitude, duration and sequencing of flows; channel maintenance; land use changes and; channel slope (natural).

5.4 Using data sets to identify influencing factors

Data sets can be used (before modelling) to identify where influencing factors may lead to hotspots of potential change. A wide range of data sets were considered including (but not limited to) LiDAR, aerial imagery, OS mapping, and Environment Agency asset data. The literature and flood data review revealed that the impacts of influencing factors are often more significant when they occur together, and therefore links between the factors were explored when considering how existing, national data sets could be used. For example, channel slope (identified using LiDAR and OS mapping) checked in combination with BGS drift geology maps and aerial imagery could be used to identify areas that are steep with erodible alluvial deposits and a lack of stabilising riparian vegetation. These areas could be potential hotspots of change.

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List of abbreviations

AEP	Annual exceedance probability
BGS	British Geological Survey
CEH	Centre for Ecology & Hydrology
CORINE	CORINE (Land Cover) 'coordination of information on the environment'
DA (grid)	Drainage area (grid)
Defra	Department for Environment, Food & Rural Affairs
GIS	Geographic information system
LiDAR	Light Detection and Ranging
OS	Ordnance Survey
REAS	River Energy Audit Scheme
SEPA	Scottish Environment Protection Agency
UK	United Kingdom

6 Appendix A: Impact of influencing factors on the geomorphological response of a river during a flood event

6.1 Local factor: Bedrock/valley confinement

6.1.1 Description

Levels of confinement differ throughout the drainage network, with a general downstream reduction in confinement. In confined, partly confined and unconfined valley settings, the channel abuts a confining margin for >90%, 10 to 90% and <10% of its length, respectively (Fryirs and others, 2016).

6.1.2 Supporting literature / flood event example

- Baker, 1977
- Dean and Schmidt, 2013
- Fryirs and others, 2016
- Joyce and others, 2018
- Miller, 1995
- O’Brien and Wheaton, 2015
- Sholtes and others, 2018
- Thompson and Croke, 2013

6.1.3 How Hey’s variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – Channel confinement can occur in steep and resistant valley margins. In these areas, the channel is limited in its ability to adjust its cross-sectional shape in response to flood flows.

Slope - Channel confinement can occur in steep and resistant valley margins. In these areas, the channel is limited in its ability to adjust its shape in response to flood flows.

Plan shape - Channel confinement can occur in steep and resistant valley margins. In these areas, the channel is limited in its ability to adjust its plan shape in response to flood flows.

Velocity – No impact.

Bed forms – No impact.

Discharge – No impact.

Input sediment load – The input sediment load could potentially be impacted by confinement if sequencing is taken into account (downstream of constriction).

Bed and bank sediment size – No impact.

Valley slope – No impact.

6.2 Local factor: Channel slope (natural)

6.2.1 Description

Slope varies naturally as a result of numerous independent variables, including:

(1) solid geology
(2) glacial history
(3) geomorphological processes such as deposition within channel or from alluvial fans/hillslope inputs
(4) tributary junctions
(5) wood jams

6.2.2 Supporting literature / flood event example

- Buraas and others, 2014
- Magilligan and others, 2015
- Montgomery and Buffington, 1997
- Thompson and Croke, 2013

6.2.3 How Hey's variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – Channel cross-sectional shape is sensitive to slope. Channels are generally narrower and shallower in steep upland areas and wider and deeper in more lowland areas. The potential response to flood events is more severe in upland/steep reaches compared to lowland/low gradient systems. However, this is often offset by other factors such as available sediment supply, channel substrate, position on the longitudinal continuum.

Slope - Steeper areas of channel have higher values of stream power available to perform geomorphic work. The potential response to flood events is more severe in upland/steep reaches compared to lowland/low gradient systems.

Plan shape - The channel tends to be more sinuous within lower gradient reaches with better connection to the flood plain, compared to steeper sections, which tend to be more confined. The potential response to flood events is likely to be less severe in lower, gradient, more sinuous reaches.

Velocity – Flow velocity is higher in steep sections of channel, which can generate more erosion and more risk of a sudden breach during a flood event (for example, embankment breaching and failure) compared to reaches with shallower gradients.

Bed forms – Coarser bed forms and typically less depositional bed forms in steeper reaches due to higher velocities. Shallower reaches typically have lower velocities, enhancing the deposition of fine sediment, creating differing bed forms. The potential response to flood events is more severe in upland/steep reaches compared to lowland/low gradient systems. However, this is often offset by the sediment size associated with the gradient of the reach. For example, coarse bedload in a steep headwater channel will have less susceptibility to bedform change.

Discharge – No impact

Input sediment load – No impact

Bed and bank sediment size – Bed material typically coarser in steeper channels due to higher velocities transporting fines. The potential response to flood events is more severe in upland/steep reaches compared to lowland/low gradient systems. However, this is often offset by the sediment size associated with the gradient of the reach. For example, coarse bedload in a steep headwater channel will have less susceptibility to modify channel substrate and bank material.

Valley slope – No impact

6.3 Local factor: Magnitude, duration and sequencing of flows

6.3.1 Description

Flow regime varies naturally as a result of numerous independent variables, including:
(1) climate
(2) geology
(3) soils
(4) topography
(5) vegetative cover
(6) river size

6.3.2 Supporting literature / flood event example

- Bizzi and Lerner, 2015
- Guan and others, 2016
- Jacobs, 2011
- Morche and others, 2007
- Sholtes and others, 2018;
- Soar and Thorne, 2011;
- Surian and others, 2009
- Wolman and Miller, 1960

In the 2009 event in the Wooler Water catchment (Northumberland), bank retreat and erosion occurred as well as reactivation of sediment sources created by the previous (2008) flood event and reworking of channel deposits. The magnitude, duration and sequencing of flows was identified as a key influencing factor (as well as the legacy of past gravel extraction and the condition of channel engineering and structure/bank protection). In the 2015 flood event in the Greta catchment (Cumbria), significant sediment deposition occurred in Keswick as a result of the magnitude, duration and sequencing of flows which conveyed significant amounts of sediment downstream.

6.3.3 How Hey’s variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – The relative morphological importance of small but regular flows events over large, infrequent events depends on channel type. Many features of alluvial rivers are shaped by flows at or near bankfull (Wolman and Miller, 1960). In large magnitude floods, geomorphic processes can result in changes to the channel width and depth, due to widening and incision. If large floods happen to occur consecutively, the impacts of the later flood may be increased.

Slope - In large magnitude floods, geomorphic processes can result in widening and incision, leading to knickpoint erosion and bed gradient changes.

Plan shape - Many features of alluvial rivers are shaped by flows at or near bankfull (Wolman and Miller, 1960), including planform and river type.

Velocity – In-channel velocity is directly impacted by the magnitude of the flood event. Larger magnitude flood events result in higher in-channel velocities, and will cause higher rates of bank erosion in rivers with erodible boundaries.

Bed forms – Rare and infrequent flood events become increasingly important as the competence required to move bed material increases. In upland areas, where large material is present, significant channel reforming floods only occur in response to extremely localised rainfall

Discharge – The magnitude, duration and sequencing of flows are key drivers of morphological change.

Input sediment load – Flooding can activate a variety of sediment sources (banks, valley sides etc.). Re-activated sediments are transferred to downstream reaches during flood events, which can significantly alter local geomorphic processes and flood risk.

Bed and bank sediment size – Large flood events may often activate a variety of sediment sources, through river bank erosion, eroding valley sides, unstable mine workings and landslides. This may subsequently alter the in-channel dominant sediment size by altering the main sediment sources.

Valley slope – No impact.

6.4 Local factor: Sediment supply and connectivity

6.4.1 Description

This includes sediment supply and connectivity in the following nested hierarchy (Harvey, 2002):

1. local (within landforms)
2. zonal (sediment transfer between landforms such as hillslope-channel connections)
3. catchment (behaviour of entire catchment with linkages along the sediment cascade)

6.4.2 Supporting literature / flood event example

- Dean and Schmidt, 2013
- Fryirs, 2017
- Harvey, 1991, 2002
- Johnson and Warburton, 2002
- Joyce and others, 2018
- Milan and others, 2012
- Morche, 2007
- Warburton and others, 2002
- Wohl and others, 2016

The 2005 flood event increased the extent of active channel deposits in the channel of the River Caldew, both through the reworking of old surfaces and the formation of new deposits from sediment supplied from upstream. Significant erosion occurred on the outside banks of meanders, while deposition occurred on the inside of bends. This effect was further accentuated as flows were deflected towards the opposite bank by deposited sediment increasing the potential for erosion.

In the Wooler Water catchment, the 2008 flood event generated adjustment involving channel enlargement (deepening and widening) and the creation of a very large number of additional sediment sources and channel deposits. Much of the sediment is currently stored in the river channel as large gravel bars. While the 2009 flood caused a significant amount of bank retreat (especially downstream of Wooler), the main effect of this flood was to reactivate sources created by the 2008 flood and rework channel deposits. This led to further bank erosion and reworking and further build-up of channel deposits.

Flooding in the Kent catchment in 2015 is reported to have initiate landslides further upstream, inputting large amounts of sediment into the channel. Kendal formed the main sediment sink, with a large reduction in channel capacity reported due to sediment deposition.

6.4.3 How Hey’s variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – Reactivated sediments deposited downstream of the source have the potential to trigger significant alteration to channel cross-sectional shape. For example, sediment deposited during flood events can cause rapid accumulation within the channel decreasing channel depth/capacity.

Slope - Significant sediment deposition in-channel during the falling limb of a flood event can locally reduce channel gradient.

Plan shape - In some cases, flooding will only cause a long-term change in the channel planform if coupled with the influx of sediments from reactivated sediment sources. Reactivated sediments are deposited downstream of the source, causing morphological change. Major geomorphic change may be concentrated at tributaries, where the sediment supply is increased.

Velocity – Increased deposition has the potential to alter flow dynamics within the channel. Increased deposition in-channel can reduce flow velocity upstream, while increasing velocity locally due to flow deflection, triggering bank scour.

Bed forms – An influx of sediments during the falling limb of a flood hydrograph can potentially alter bed morphology, that is, triggering a change from a single thread channel to a braided channel.

Discharge – No impact

Input sediment load – Flooding can activate a variety of sediment sources (banks, valley sides). Re-activated sediments are transferred to downstream reaches during flood events, which can significantly alter local geomorphic processes and flood risk.

Bed and bank sediment size – Flooding may often activate a variety of sediment sources, through river bank erosion, eroding valley sides, unstable mine workings and landslides. This may subsequently alter the in-channel dominant sediment size by altering the main sediment sources.

Valley slope – No impact

6.5 Local factor: Large wood and riparian vegetation

6.5.1 Description

This includes:

(1) stabilising effects, such as:
  (i) vegetation growth reducing erosion
  (ii) vegetation growth enhancing sediment storage
  (iii) large wood enhancing sedimentation and decreasing flooding
(2) destabilising effects, such as:
  (i) large wood enhancing erosion and increasing flooding

6.5.2 Supporting literature / flood event example

- Buffington and Montgomery, 1993
- Green, 1955
- Marcus and others, 2002
- Morche and others, 2007
- Surian and others, 2016
- Viles and others, 2008
- Wohl and others, 2019
- Wondzell and others, 1999

In the 2005 flood event, bank erosion on the River Caldew was most significant where trees had collapsed, either during or prior to the events (for example, at Hawksdale). On straighter sections of channel, trees collapsing often caused channel widening and sediment deposition upstream.

In the 2009 event on the River Derwent, the collapse of a large wood jam was highlighted as a potential (although not definite) cause of the creation of a chute channel (partial avulsion), coupled with coarse sediment deposition. Bank erosion was also attributed to the degree of vegetation cover before the event.

6.5.3 How Hey’s variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – In-channel woody material alters bankfull wetted perimeter, hydraulic radius and maximum flow depth, causing locally significant increases in shear stress and erosion/scour during flood events (i.e. in narrowed sections), as well as local flow impoundment and sediment aggradation upstream. Failure of riparian trees caused by bank erosion can lead to widened cross sections.

Slope - No impact.

Plan shape - In-channel woody material has the potential to trigger changes in channel sinuosity and meander arc length. For example, it may can deflect flows and trigger erosion on opposite banks, encouraging the channel to increase its sinuosity.
Vegetation can stabilise channel banks and hillslopes, which can reduce the supply of sediment to downstream reaches, influencing the resulting channel types.

Velocity – In-channel woody material will lead to increased velocities during flood events in narrowed areas. This can exacerbate erosive or depositional processes during flood events.

Bed forms – Large wood creates localised changes in bed form due to hydraulic changes in vicinity of the structures.

Discharge – No impact.

Input sediment load – Vegetation can stabilise channel banks and hillslopes, which can reduce the input sediment load to the channel.

Bed and bank sediment size – No impact.

Valley slope – No impact.

6.6 Local factor: Floodplain infrastructure

6.6.1 Description

This includes:

(1) flood related flood plain infrastructure
  (i) embankments
  (ii) flood walls
  (iii) flood storage areas
  (iv) land raising for flood management
(2) other flood plain infrastructure:
  (i) transport infrastructure
  (ii) buildings
  (iii) services
  (iv) pylons

6.6.2 Supporting literature / flood event example

- Gilvear and others, 1994
- Johnson and Warburton, 2002
- Joyce and others, 2018

- Paine and others, 2002

In the 2008 flood event in Northumberland, the most severe erosion recorded in the Breamish catchment occurred in a 1 km stretch of the River near Brandon footbridge, where the flood plain is most confined. A road, ford, footbridge and electricity pylon were at risk due to significant channel erosion.
In the same flood event, avulsion, reactivation of palaeo channels, scouring of the flood plain and redeposition of sands and gravels occurred due to flood plain infrastructure (as well as past alignment and asset failure).
In the 2009 flood event in the Cocker catchment (Cumbria), bank erosion resulted in channel enlargement. Flood plain infrastructure (embankment) was identified as a causal factor (as well as past realignment and sediment supply and connectivity.

6.6.3 How Hey's variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – Flood plain infrastructure can alter the bankfull wetted perimeter, hydraulic radius and maximum flow depth during flood events. For example, embankments can confine flood flows to the channel. This can cause widening through erosion, which can undermine structures.

Slope - No impact.

Plan shape - Infrastructure on the flood plain can restrict and confine morphological adjustment, that is planform migration, during flood events, impacting on the ability of the channel to adjust its channel sinuosity and associated meander arc length.

Velocity – Restricted/confined flows lead to local increase in flow velocity where flows are concentrated through an unusually small flow area. This may cause channel widening in confined areas, which can undermine structures. Sediment deposition may occur downstream of constrictions where flow velocities are reduced, as well as upstream within impoundment zones.

Bed forms – Local increases in velocity and shear stress caused by flow constriction during flood events could alter sediment entrainment and transport, scouring existing bed forms, enhancing downstream sediment transfer. This could lead to exacerbated bed incision, with less stability within the channel.

Discharge – No impact

Input sediment load – No impact

Bed and bank sediment size – The bank is often modified with hard protection in areas of flood plain infrastructure, preventing adjustment.

Valley slope – No impact.

6.7 Local factor: Channel modification

6.7.1 Description

This includes historic works that have altered channel dimensions and planform, such as:
(1) channelisation/ straightening

(2) realignment

6.7.2 Supporting literature / flood event example

- Eaton and Lapointe, 2001
- Death and others, 2015
- Downs, 1994
- Hooke and Redmond, 1989
- Hooke and Redmond, 1992

In the 2008 flood event in Northumberland, avulsion, reactivation of palaeo channels, scouring of the flood plain and redeposition of sands and gravels occurred due to past realignment (as well as flood plain infrastructure and asset failure).
In the 2009 flood event in the Cocker catchment (Cumbria), bank erosion resulted in channel enlargement. Past realignment was identified as a causal factor (as well as flood plain infrastructure (embankment) and sediment supply and connectivity.
In the Wear catchment (North east England) it was noted that the 2015 flood event resulted in acceleration of pre-existing, significant erosion in the vicinity of a footbridge near Frosterley. Past modification of the channel was a key influencing factor (as well as the presence of infrastructure and sediment supply and connectivity).
In the Kent catchment in the 2015 flood event, bank erosion was noted to be exacerbated in the vicinity of bank protection that prevents the natural adjustment of the channel.

6.7.3 How Hey's variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – Works, such as channelisation, straightening or realignment, that involve altering the channel width and/or depth will alter bankfull wetted perimeter, hydraulic radius and maximum flow depth. This has the potential to cause or exacerbate incision, bank undercutting/erosion and scour during flood events. During flood events, for example, reaches that have been widened/deepened experience elevated in-channel velocities as water is contained within the channel, rather than spilling onto the flood plain. Impacts of the modification on morphological processes can extend beyond the modified reach. Channel erosion upstream of the modified reach may be accentuated during flood events and eroded sediment may be deposited in downstream reaches.

The opportunity for morphological adjustment of a channel reach during flood events may be extremely limited by channelisation, straightening or realignment due to hard bank protection. In these situations, floodwaters are quickly conveyed downstream; therefore, the channel response to floods may be more visible downstream. Channel degradation upstream of the modified reach may be accentuated during flood events and sediment deposition may occur downstream

Slope - Channel modification can also potentially impact channel slope, by increasing or decreasing the channel length. Modified rivers often have a steeper slope than the original channel (due to a shorter channel length). This means that stream power is increased, potentially leading to incision, which is exacerbated during flood conditions.

Plan shape - Channel modification is likely to result in a direct change in planform. Such changes can make the channel more vulnerable to erosion or deposition during a flood event. For example, a straightened channel is likely to cause elevated in-channel velocities (due to the associated decrease in gradient) and therefore is likely to be

more responsive to flood events in terms of erosion. Works that involve altering the channel width/depth have the potential to trigger changes in channel sinuosity and meander arc length. For example, an overwide channel may cause sediment deposition, which can deflect flows and trigger erosion on opposite banks, encouraging the channel to increase its sinuosity.
If deposited sediment forms a plug during a flood event in a realigned channel, channel avulsion may occur as the channel attempts to morphologically adjust back to its natural state. Water that spills onto the floodplain may flow in palaeochannels.

Velocity – Works that involve altering the channel width and/or depth will lead to increased or decreased velocities in-channel during flood events. This can exacerbate erosive or depositional processes.
Realigned/channelised rivers often have a steeper slope than the original channel (due to a shorter channel length). This means that in-channel velocity is increased, potentially leading to increased bank erosion during flood conditions.

Bed forms – Works that involve altering the channel width/depth will potentially impact on the development of in-channel bedforms. For example, a widened/deepened channel, with faster flow velocities may flush material through the system and prevent the accumulation of organised bedforms, that is, features such as riffles and gravel bars. This could lead to a less structured bed that is less resilient to erosion during flood events.

Discharge – No impact

Input sediment load – No impact

Bed and bank sediment size – Works that involve altering the channel width/depth will potentially impact on the composition of the bed sediment, due to alterations in the flow hydraulics and sediment transport regime. For example, in narrowed channels, the in-channel velocity and stream power will be increased during flood events in comparison to the pre-narrowed channel increasing the potential for bed and bank scour. However, this would be dependent on flood plain connectivity and the potential for out of bank flows to occur.

Valley slope – No impact

6.8 Local factor: Channel maintenance

6.8.1 Description

This includes:

(1) works to remove accumulated sediments (fine sediments, as well as coarser cobble/gravel sized material)
(2) vegetation management and removal

6.8.2 Supporting literature / flood event example

- Hooke and Redmond, 1989
- Sear and others, 1995
- Sear and others, 2010
- Thorne and others, 2011
- Westlake, 1975

- Wohl and others, 2019

In the 2009 event in the Wooler Water catchment (Northumberland), bank retreat and erosion occurred as well as reactivation of sediment sources created by the previous (2008) flood event and reworking of channel deposits. The legacy of past gravel extraction was identified as a main influencing factor (as well as the condition of channel engineering and structure/bank protection and the magnitude, duration and sequencing of flows).

6.8.3 How Hey’s variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – channel maintenance and dredging can alter the bankfull wetted perimeter, hydraulic radius and maximum flow depth. These changes to the channel capacity can substantially impact the potential morphological change caused by a flood event, both at the site as well as downstream. For example, sediment dredging can potentially lead to an over-deepened channel with poor flood plain connectivity, in which flood flows are confined. This can lead channel incision and bank collapse.

Slope - Slope is often reduced in the dredged area, potentially reducing energy levels and encouraging deposition of finer materials. Dredging also has the potential to initiate knickpoint migration upstream, causing a change in reach slope beyond the immediate dredged reach.

Plan shape – No impact.

Velocity – Removing sediment/vegetation will lead to deeper, faster flows, again increasing the potential for morphological change during a flood event due to the risk of increased bank scour.

Bed forms – Removing sediment can destroy bedforms, leading to unstable beds and banks that are less resistant to scour during flood events.

Discharge – No impact.

Input sediment load – No impact.

Bed and bank sediment size – Removing bed material can potentially alter the grain size distribution of the bed, which may reduce the critical shear stress for entrainment (that is, removal of coarse armour layer leaves the bed more vulnerable to scour), exacerbating bed erosion during flood events.

Valley slope – No impact.

6.9 Local factor: In-channel structures

6.9.1 Description

This includes:

(1) bounding structures on one boundary of the channel only such as bank or bed protection which prevent lateral migration or bedform creation and which may become undermined/ outflanked especially in major floods
(2) bounding structures on both sides of the channel such as culverts, parallel bank protection or bridge abutments which may constrict flow leading to increases in velocity
(3) structures that partly block the channel or effect part of the cross-section form, such as outfalls, piers, groynes, partly-broken weirs, which tend to cause scour

channel-spanning structures such as trash screens or weirs that pond and cause aggradation upstream and may lead to sediment starvation

6.9.2 Supporting literature / flood event example

- Fryirs 2017
- Jakob and others, 2003
- Surian and others., 2016
- Ward and Stanford, 1995

In the 2005 flood event, the former Cummersdale Weir on the River Caldew was a significant factor in the rivers response to the flood event. Sediments were deposited in the impounded zone immediately upstream of the weir, causing bank retreat. Downstream, sediments were reactivated as a point bar was cut through by migration of the main channel.

On the River Kent in 2005, the trash screen by Stock Beck tributary was blocked with debris, causing water to back up and initiating excessive scour upstream.
In the 2009 flood in Cumbria, extensive areas of gravel and fine sediment deposition occurred upstream of weirs located in the Staveley reach of the River Kent.
In the 2009 event on the River Derwent, the presence of hard bank protection was highlighted as a potential (although not definite) cause of the creation of a chute channel (partial avulsion), coupled with coarse sediment deposition and knickpoint erosion.

In the Wear catchment (North-east England) it was noted that the 2015 flood event resulted in acceleration of pre-existing, significant erosion in the vicinity of a footbridge near Frosterley. Infrastructure was a main influencing factor (as well as past modification and sediment supply and connectivity).

6.9.3 How Hey's variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – In-channel structures alter bankfull wetted perimeter, hydraulic radius and maximum flow depth, causing locally significant increases in shear stress and erosion/scour during flood events (through bridge openings), whereas other structures (such as weirs) cause local flow impoundment and sediment aggradation upstream.

Slope - In-channel structures alter channel slope. For example, weirs cause impoundment, impacting local stream power. This may mean that during flood events, the system is less competent to flush sediments through the system, leading to aggradation upstream, coupled with increased potential for channel incision downstream during flood events if sediment transfer is significantly impacted.

Plan shape - In-channel structures such as culverts and trash screens may get blocked by debris. This may cause water levels to back up and the main channel to divert its course.

Velocity – Restricted/confined flows lead to local increase in flow velocity and erosion. This may occur, for example, downstream and around the abutments of bridges. Impoundment can cause sediment aggradation upstream.

Bed forms – Local changes in velocity and flow dynamics caused by in-channel structures could alter sediment entrainment and transport, altering the development of channel bed forms. This could lead to exacerbated bed erosion, with less stability within the channel bed, or excessive sedimentation where flow velocities are reduced.

Discharge – No impact

Input sediment load – No impact

Bed and bank sediment size – The bed and bank are often modified with hard protection near in-channel structures (such as concrete sills, headwalls), which prevents adjustment during flood events. The bed sediment size distribution may also change near the structure due to changes in flow dynamics and velocity. For example, a weir impounds flows, decreasing velocities, leading to sediment deposition upstream and potentially a decrease in sediment transfer downstream. This could lead to an increase in the finer fractions of the grain size distribution upstream, and a decrease downstream, where the finer fractions are winnowed from the bed.

Valley slope – No impact

6.10 Local factor: Asset failure

6.10.1 Description

This includes:
(1) breaching / overtopping of flood defences
(2) outflanking of hard bank protection
(3) failure of hard bank protection,
partial or full collapse of in-channel structures such as weirs or bridge

6.10.2 Supporting literature / flood event example

- Johnson and Warbuton, 2002
- Death and others, 2015
- Gilvear and others, 1994
- Jarrett and Costa, 1986
- Paine and others, 2002
- The Guardian, 2019

In the 2008 flood event in Northumberland, flood defences were overtopped in the Till catchment, which triggered flood bank failure/breaching in some locations. Avulsion, reactivation of palaeo channels, scouring of the flood plain and redeposition of sands and gravels occurred in the Glen and Breamish catchments in the same flood event. A key influencing factor was asset failure (as well as flood plain infrastructure and past realignment).

In the 2009 event in the Wooler Water catchment (Northumberland), bank retreat and erosion occurred as well as reactivation of sediment sources created by the previous (2008) flood event and reworking of channel deposits. The condition of channel engineering and structure/bank protection was identified as a key influencing factor (as well as the legacy of past gravel extraction and the magnitude, duration and sequencing of flows).

6.10.3 How Hey’s variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – During flood events, flood defences may be overtopped, which can trigger bank failure and breaching in some locations, along with resultant rapid alterations to the channel cross-sectional shape. Turbulence created from altered flow patterns around failed bank modification or flood defences can lead to elevated scour and erosion.

Slope - No impact

Plan shape - Where confined by flood defences, high velocity flows may cause bank erosion during flood events. This may cause damage and/or failure of the defences, as the channel attempts to erode its boundaries and adjust its morphology, that is become more sinuous in planform. This process is accentuated by elevated scour patterns when defences or hard bank protection is outflanked.

Velocity – During flood events, flood defences may be overtopped, which can trigger bank failure and breaching. Locally elevated flow velocities can lead to flood plain scour and deposition of sediment on the flood plain.

Bed forms – No impact

Discharge – No impact

Input sediment load – No impact

Bed and bank sediment size – Failure of hard bank protection or flood defences essentially represents a change in bank sediment size from hard material to natural material. This means that the bank becomes ‘erodible’, often accentuated by elevated scour during flood events

Valley slope – No impact

6.11 Local factor: Land use changes

6.11.1 Description

This includes:
(1) urbanisation
(2) deforesting for agriculture
(3) forest management

(4) removal of vegetation

6.11.2 Supporting literature / flood event example

- Hooke and Redmond, 1989
- Hooke and Redmond, 1992
- Joyce and others, 2018

6.11.3 How Hey's variables (dependent or independent) are impacted by the local factor

Cross-sectional shape – No impact.

Slope - No impact.

Plan shape - No impact.

Velocity – No impact.

Bed forms – No impact.

Discharge – Urbanisation may increase surface run-off and discharge in the channel, which can cause high rates of downstream bank erosion as the channel adjusts to accommodate higher flows. These effects are usually more localised.

Input sediment load – Widespread land use change may cause increased channel sensitivity throughout a large portion of the catchment. Land use changes which decrease infiltration rates and increase flood plain erosion, such as deforesting for agriculture, may increase the sediment load and deposition in the channel during flood events.

Bed and bank sediment size – Bed sediment size could be altered by a change in sediment sources. For example, deforestation within the catchment could increase the inputs of fine sediment within the channel.

Valley slope – No impact.

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