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Understanding river channel sensitivity to geomorphological changes

Developing and evaluating methods to identify erosion, transport and deposition on a national scale

FRS17183/R2

Flood and Coastal Erosion Risk Management Research and Development Programme

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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 understand where river channels are sensitive to change in both normal and extreme flows in England and Wales, and to better understand the factors that influence that change.

Research approach

This study is documented in 4 reports:

- Report 1: Literature review and understanding factors that influence river channel change (FRS17183/R1)
- Report 2: Developing and evaluating methods to identify erosion, transport and deposition on a national scale (this report, 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)

This report describes the tested and evaluated methods and models used to identify in-channel geomorphological activity under both current and future river flow scenarios. Methods were evaluated based on their potential to be applied on a national scale, looking at their strengths and weaknesses, and considering whether climate change is, or could be, factored into the method. The intention is to identify what data could be used to identify ‘hotspots’ of geomorphological activity and to inform strategic decisions around channel maintenance planning and environmental management.

Multi-criteria analysis was used to select 4 methods to take forward to project trials. The shortlisted methods were:

- ST:REAM (Sediment Transport: Reach Equilibrium Assessment Method)
- CAESAR-Lisflood
- Half-yield method
- Shear stress data mining method

For the project trials, a list of catchments in England and Wales was suggested based on the availability of fluvial audit data sets and suggestions from the project steering group. A multi-criteria analysis was used to select 3 catchments to use in the project trial phase. The final 3 catchments selected were:

- River Kent (Cumbria)
- River Stour (Dorset)
- River Wharfe (North Yorkshire)

Incorporating influencing factors into the trialled methods

The project has considered how the influencing factors identified in Report 1 could be incorporated into the methods. The influencing factors are valley confinement, channel slope, flows (magnitude, duration, sequencing), sediment supply, large wood and riparian vegetation, flood plain infrastructure, channel modification, channel maintenance, in-channel structures, asset failure and land use changes.

For ST:REAM, half-yield and the shear stress data mining methods, an analysis was carried out to identify how each influencing factor could be incorporated (if considered feasible) by adding in extra detail following the initial model runs. This would essentially result in a 2-stage approach, for which 2 levels of results would be generated. In the first stage, national scale model runs would be carried out. In the second stage, as well as the national scale model, local influencing factors would be investigated, from which an updated data set of results would be produced.

In contrast, the CAESAR-Lisflood model allows the majority of the influencing factors to be incorporated within the model setup. The influencing factors are broadly grouped into 3 categories: structures that are, in theory, fixed and immovable, actions that lead to channel modification, and features that are incorporated into the method.

A high-level analysis of whether identifying and incorporating influencing factors into the methods could be automated has been carried out. This found that national scale GIS data sets, such as LiDAR, are likely to present the greatest opportunity to automatically identify and incorporate influencing factors. Being able to incorporate these influencing factors using an automated process depends on the method and the specific influencing factor.

Findings

The trial phase involved applying the methods to the test catchments, allowing the project team to gain a comprehensive understanding of the strengths and weaknesses of the methods in practice. A further, more extensive but computationally efficient, trial was carried out on the shear stress data mining method to create, for the first time, a pilot national data set for England and Wales.

This could be used to target more detailed geomorphological modelling using the more complex landscape elevation model (LEM) software such as CAESAR-Lisflood. This can be used to indicate long-term changes in bed elevation and morphological change, and quantities of sediment change.

Erosion could be used to indicate where lateral change may occur, for example, representing a hazard to flood plain infrastructure, whereas deposition could inform where channel capacity may be compromised, causing a greater frequency of over-bank flooding.

Based on the findings, computationally simple methods can be used to identify hotspots of potential channel change. If combined with data on factors influencing change, the likelihood of erosion and deposition could be identified. This could be achieved through a model decision support framework.

Recommendation

It is recommended that next steps for this research would be to carry out further user analysis on how such data on river channel change would support flood risk and environment management before selecting one or more methods for an operational national scale data set. A model decision support framework could be explored, which could allow users to select results most appropriate to their application and local catchment conditions.

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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.

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1 Introduction

1.1 Background

River channels physically change over time: natural processes such as erosion and sedimentation may cause channels may widen or narrow; to become shallower or deeper; or they may cause a river may move to a new location. These changes can alter flood risk. Therefore, in order to manage flood risk we need tools and data to consistently account for such changes in flood risk assessments or operational activities.

Climate change is predicted to increase the frequency of floods across England and Wales in the coming decades. This may not only increase the frequency of smaller floods, but it is likely to cause extreme flooding to occur more often. These changes could alter river behaviour and flood risk.

Across England and Wales we therefore need to understand more about where and when an increase in flooding may trigger changes in geomorphological activity (erosion, deposition and transport), 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.

It is important to note that while channel change can alter flood risk, it can also provide benefits for human society. As channels adjust and evolve over time they create new habitats, which supports a healthy biologically diverse aquatic ecosystem. Channel changes can also provide ecosystem services such as slowing the flow to reduce flood risk downstream. Channel changes allow natural adaptation to climate change: processes such as erosion or deposition re-sculpt the channel to accommodate higher or lower flows. The project outputs increase our understanding of the natural processes in order to implement management in a way that values the benefits as well as managing the risks.

This commission identified ways to assess physical changes and associated flood risk in rivers in England and Wales. Different methods were tested 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).

This 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 2: Developing and evaluating methods to identify erosion, transport and deposition on a national scale.

1.2 Report aims

This report summarises the work completed to test and evaluate methods and models to identify in-channel geomorphological activity (erosion, transport and deposition) across England and Wales, both under current conditions and with future climate change.

It is intended that the methods could later be used to support national decisions, particularly in identifying hotspots where channel changes are more likely and need considering locally.

The objectives are to:

- identify, list and compare existing methods
- develop potential new approaches
- describe what could be gained from incorporating locally detailed hydrological and sediment models into these approaches
- identify appropriate data sources that predict the impact of climate change on river flows, and describe how this data could be incorporated into the method, using the latest available predictions of climate change
- describe the feasibility of using these methods to produce national scale information on river hydraulics and behaviour
- shortlist methods that would be best suited to achieve the aims of the report
- select test catchments to trial the shortlisted methods
- apply the shortlisted methods in the test catchments and review the outputs
- document a clear workflow and a description of tools that would be used to replicate the trialled methods

2 Identifying potential methods

2.1 Overview

A literature review revealed a number of existing methods for identifying erosion and sedimentation processes in rivers (see Figure 2.1). The existing methods can be broken down into 2 broad categories: stream power and hydrodynamic modelling approaches. The methods are outlined below (the following sections of this report examine each of these approaches in detail).

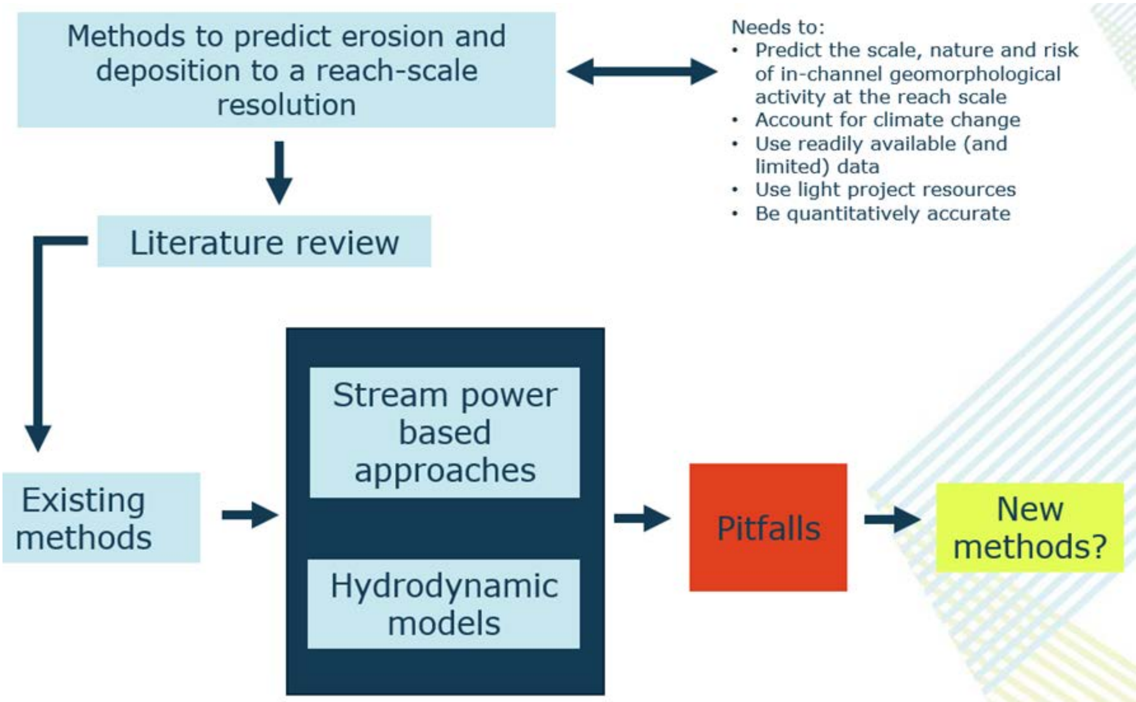


Figure 2.1 Report 2 methodology

2.1.1 Stream power approaches

Stream power characterises the driving force available for transporting sediment. The term stream power was originally used by Bagnold (1960, 1966), who defined stream power as the product of the river discharge, slope and weight of water. The capacity of a river to do geomorphological work, that is to change the position or morphology of the channel, can be characterised by the availability of stream power to entrain and transport sediment.

The methods reviewed use stream power as an independent variable that affects geomorphic forms and processes, such as sediment transport and deposition.

2.1.2 Stream power approaches

The following stream power approaches were considered in this project:

- ST:REAM - Parker and others (2015)
- map-derived stream power - Bizzi and Lerner (2015)
- REAS - Soar and others (2017)

2.1.3 Hydrodynamic modelling approaches

Hydrodynamic modelling is a type of simulation using in-channel/flood plain elevation data and hydrograph inflows to drive a computer model of hydraulics where flow varies over time. Examples include HEC-RAS, JFlow, Lisflood-FP and TUFLOW. Hydraulic modelling is an important tool for determining flood hazard and flood risk at the local scale.

Industry-standard hydrodynamic software such as HEC-RAS (with a 2-dimensional hydromorphology version in development), Flood Modeller and TUFLOW have sediment/morphology modules and are widely applied for river modelling studies. CAESAR-Lisflood is a landscape evolution model that combines a hydrodynamic flow model (Lisflood-FP) with a geomorphic model (CAESAR) to simulate erosion and deposition in river catchments and reaches over time scales from hours to thousands of years.

Although widely used in local studies, the potential to set up and run HEC-RAS, Flood Modeller and TUFLOW models at a national level for modelling sediment processes is presently unfeasible due to the setup time, data input requirements and model run times. In contrast, CAESAR-Lisflood can potentially be used to model sediment processes over entire catchments, and has been used in over 60 peer-reviewed studies across the world (Skinner and Coulthard, 2017). Consequently, CAESAR-Lisflood was selected to be considered in this project.

Case study examples (detailed in Appendix A) describe where hydrodynamic modelling and geomorphological assessment methodologies have already been used to understand local impacts of channel change on flood hazard (discharge, flood extent, velocity, depth, and probability of flooding). No further modelling has been carried out for this project. The approaches described constitute locally detailed studies and could therefore only be applied at a reach to catchment scale (for example, over lengths from hundreds of metres to a few kilometres).

2.1.4 Hydrodynamic modelling approach

The following hydrodynamic modelling approach was considered in this project:

- CAESAR-Lisflood – Coulthard and others (2013)

2.1.5 Future hydrodynamic modelling approaches

The desire to integrate hydraulic modelling with sediment transport processes is leading to the development of new codes that can be used to study and predict geomorphological processes. Although not available at present as ‘ready-to-run’ software, they illustrate the drive within both industry and academic research fields to develop techniques that can be used to study erosion and deposition processes in rivers.

For example, Guan and others (2016) tested and integrated hydraulic and morphological modelling in a gravel bed stream in the north west of England. This involved applying a research code that incorporated sediment fluxes, erosion, deposition and some secondary circulation effects within a 2D, depth-averaged flow model. The resulting hydrodynamic model was used to assess morphological change around a bend in a gravel-bed river (River Greta, Cumbria), which highlighted the importance of including correction terms for secondary/helical circulation if using a 2D depth-averaged model.

In Reid and others (2018) a related, but simpler approach was used to see whether a 2D flow model could be useful in understanding the evolution of bars in a high energy gravel-bed river. Multiple flood events of increasing magnitude (from a mean annual flood through to an extreme 1/100 annual exceedance probability flow) were simulated using JFlow. By extracting information about modelled flow depths and velocities, Reid and others (2018) were able to calculate and map out an index of erodibility, based in a ratio of bed shear stresses. The model results showed that the bars within the river channel evolve in response to different flood events. The analysis also showed that the shape of the surrounding valley and flood plain influences the patterns of bar evolution, highlighting the need to consider the channel morphology in the context of a wider flood plain system.

The research interest in this field is likely to lead to the development of new codes in the future that may be suitable for examining the geomorphological processes at a national scale.

2.1.6 Future hydrodynamic modelling approaches

The potential for developing new methods was explored as part of this project and 2 new methods were developed. The first was developed by Dr Philip Soar (University of Portsmouth, part of JBA Consulting's project team) based on his knowledge of the pitfalls of the existing methods. The second was developed by Dr Barry Hankin (JBA Consulting) as a way of using readily available, but currently underused, national scale data sets.

The following new approaches were added to the long list to be considered in this project:

- Half-yield method – Dr Philip Soar, University of Portsmouth
- Shear stress data mining method – Dr Barry Hankin, JBA Consulting

2.1.7 Summary

An overview of the 6 methods long-listed for the trial phase, along with their main strengths and limitations are explored in more detail in the following sections. These provide an overview of each method, the input data sets required, example outputs and the strengths and weaknesses of each approach.

2.2 Method 1: ST:REAM (Parker and others, 2015)

2.2.1 Overview

ST:REAM (sediment transport: reach equilibrium assessment method) is a reach-based, stream power balance approach for predicting river channel adjustment. Alluvial channel adjustments are driven by imbalances in the transfer of channel-forming sediment through the fluvial system. Geomorphological activity is associated with reaches that have a significant imbalance between the quantity of sediment input to the reach (supply) and the quantity that can be transferred downstream (capacity). If supply exceeds capacity, the reach is likely to be dominated by depositional processes. Conversely, if capacity exceeds supply, the reach is likely to be dominated by erosional processes. The theory only considers bedload transport and channel bed erosion/incision, rather than lateral bank erosion.

The approach is based on calculations of unit bed area stream power derived from remotely sensed slope, width and discharge data sets. It applies a zonation algorithm to values of stream power that are spaced every 50 m along the catchment network in order to divide the branches of the network up into relatively similar reaches. ST:REAM then compares each reach value with the stream power of its upstream neighbour in order to predict whether or not the reach is likely to be either erosion or deposition dominated. The stages incorporated within the modelling approach include calculating stream power across the catchment, delineation of reach boundaries within the catchment network, and calculating reach stream power balances. When applying ST:REAM to the River Taff (UK) the method correctly predicted the status of 87.5% of sites within the Taff catchment that field observations had defined as being either erosion or deposition dominated.

2.2.2 Data sets

The method requires the following data sets:

- OS Open Rivers (Ordnance Survey, open data) or Digital River Network (Centre for Ecology and Hydrology, licensed data) Shapefile
- Q2 grid (Centre for Ecology and Hydrology, licensed data)
- drainage area grid (Centre for Ecology and Hydrology, licensed data)
- integrated height model 2 m resolution digital terrain model (Environment Agency, licensed data)

2.2.3 Overview of method

The main steps in applying the method are:

- River channel widths were obtained from the water theme within the OS Mastermap Topography Layer (Edina, 2014).
- The ST:REAM approach involves calculating unit bed area stream power across the river channel network at a series of separate points spaced 50 m apart along the branches of the river catchment network. To establish the topology of the river catchment network and the location of the points along the network, it was necessary to apply a series of spatial analysis techniques on the OS Land-form Profile contour and spot height data.
- The mean annual maxima flood (QMED) was selected as the representative flow discharge. A power regression was established between QMED and drainage area across the catchments (as suggested by Knighton, 1999). This relationship was then used, along with the drainage area raster data set to predict the QMED for each of the points across the river catchment network.
- Channel bed slope was approximated by dividing the DEM-based elevation drop between that point and its downstream neighbour by the downstream distance between the 2 points (50 m).
- ‘Functional’ reach boundaries were defined using Gill’s (1970) global zonation algorithm. The algorithm uses an iterative analysis of variance approach.
- The unit bed area stream power balance was calculated by dividing the unit bed area stream power of the reach in question by the unit bed area stream power of its immediate upstream neighbour (or upstream neighbour if the reach was immediately downstream of a confluence).

- Thresholds for erosion/deposition dominated status were defined using the lower/upper quartile boundary of the stream power balance, respectively.

2.2.4 Outputs

Reaches classified as erosion or deposition dominated based on thresholds of stream power balances (Figure 2-2). The outputs are based on the potential for geomorphic change, as the method does not account for sediment supply.

The sequences of stream power balances may be interpreted as trends in potential river channel sensitivity to change/response, where large ratios may reveal areas of concern where further investigation is warranted.

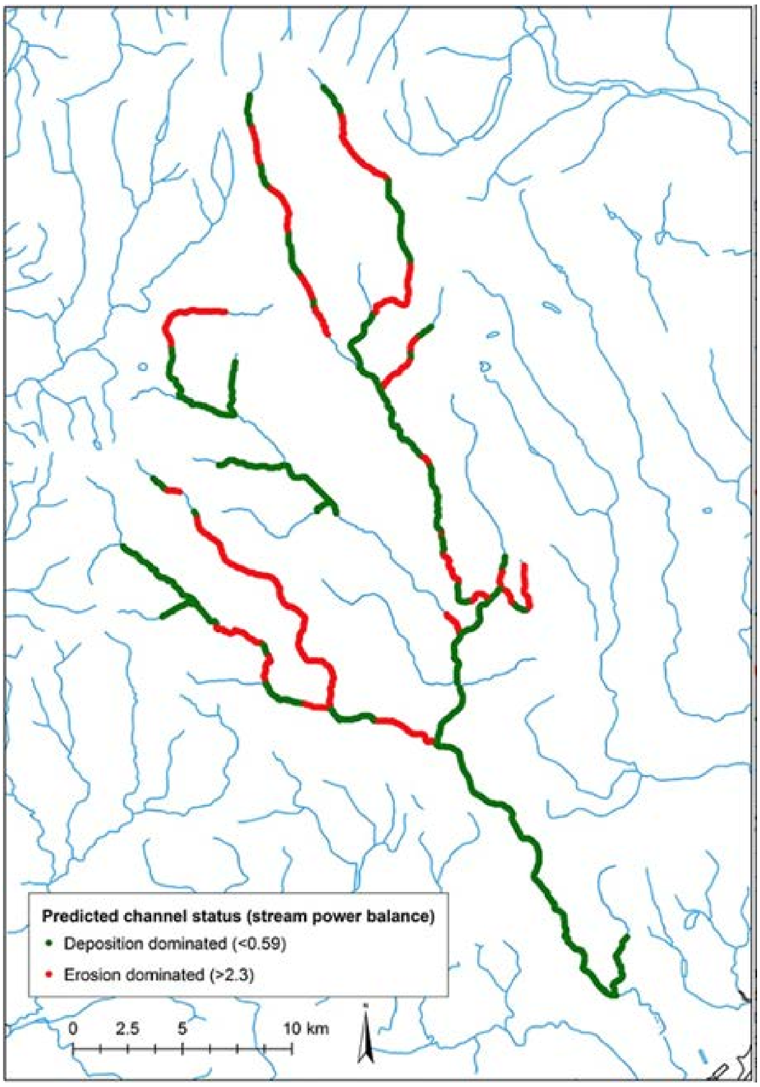


Figure 2-2 Output from ST:REAM, reproduced from Parker and others, 2015.

2.2.5 Strengths

- Uses relatively simple techniques and few resources, as well as readily available data sets. ST:REAM recognises that an applied tool should need little data to be practically applied.
- The method is fully coded up with a user guide and can be used with minimal training.

- The method has been trialled by the Scottish Environment Protection Agency (SEPA) nationally and judged to be reasonably successful. Following these trials, SEPA applied the method to all rivers in Scotland to classify and map reaches as being characterised by erosion, deposition or sediment balance. SEPA currently uses the outputs in desk assessments for regulation and restoration as well as strategic support for flood risk maps.
- Provides a science-based approach for examining local sediment problems and the risks associated with different options for sediment management within the wider context of the catchment.
- Method could provide a broad understanding of catchment-scale sediment transfer systems nationally. At present, there is no method for considering sediment dynamics at the catchment scale in England and Wales due to data and operational constraints.

2.2.6 Weaknesses

- There is some uncertainty in the measurement of parameters used to calculate stream power for points across a catchment network (Bizzi and Lerner, 2013).
- There is significant uncertainty regarding the method of measuring channel slope from DEMs (Vocal Ferencevic and Ashmore, 2012).
- The method used to estimate the QMED values for points across the catchment is based on an empirical relationship and will not account for local variability.
- The outputs are ratios of stream power between contiguous reaches. A potential problem with any ratio-based approach is that huge ratios can be derived but for very small values. As a non-linear measure, results might not always be representative of 'actual' differences between reaches.
- If there are width changes between reaches, comparing 'specific' stream power between reaches as opposed to 'total' stream power, or energy can, in some cases, be misleading. For example, it is possible for specific stream power to balance between adjacent reaches of markedly different channel width, whereas total stream energy, power and, critically, sediment yield would reveal notable imbalances (Soar and others*,* 2017).
- Simplifications within the model include the following assumptions: that the rate of sediment transport out of a reach is directly related to its specific stream power; that the supply of sediment into a reach is directly related to the stream power of its upstream neighbour(s); that the model represents a snapshot of a system that in reality evolves over time and is influenced by feedback; and that the model represents the watercourse as reach-based when in reality the channel varies continuously across space.
- Stream power calculations in general do not take into account sensitivity of the channel boundary to change, sediment supply limitations, structures that disrupt continuity beyond the local scale, channel evolution/recovery in response to recent or historical influences and non-channel sediment inputs related to bank erosion, planform change and run-off.
- Presence of bedrock could yield misleading results and would need to be identified with site visits or a suitable data source, such as fluvial audit data or aerial imagery.
- ST:REAM's reach-based nature means that its outputs are sensitive to the reach boundaries that are identified. This is potentially a subjective element of

the method and requires data to 'ground-truth' the reach boundaries in the form of fluvial audit data or similar.

- The method relies on identifying thresholds to distinguish between erosion or deposition dominated reaches. These will be different for each catchment, with results /trends potentially highly sensitive to the threshold set.
- The method addresses in-channel imbalances in stream power so that imbalances in bed material transport can be suggested. However, the method does not include sediment 'source' explicitly, rather it makes a comparison between sediment transporting 'capacity' at a location with sediment transporting 'capacity' in the neighbouring upstream reach. In addition, the model only considers sediment sourced from the channel bed. No account is made for sediment derived from bank erosion, catchment run-off or colluvial inputs.
- ST:REAM currently uses QMED as the representative flow discharge. The potential of using a range of flows to incorporate the impact of the high magnitude, low frequency events within ST:REAM was considered as an alternative to relying on a single QMED value. Advice was sought from SEPA as it had previously carried out a trial to investigate the feasibility of using a set of flow duration curves (created using Low Flow 2000) into ST:REAM, replacing the QMED as the discharge factor. Overall, SEPA found the process time consuming. It felt that while this could be done for one catchment, it is unfeasible to automate a method that could be used on a national scale. SEPA also reported that the results, in terms of erosion, deposition and balance, from ST:REAM based on flow duration curves were not very different from those extracted using QMED.

2.3 Method 2: Map-derived stream power (Bizzi and Lerner, 2015)

2.3.1 Overview

The method uses map-derived information on total and specific stream power to identify dominant processes within the channel (erosion, transport or deposition). Previous studies have used specific stream power to identify a threshold for channel stability. Two gravel bed single-thread English rivers were used as case studies; the River Lune and the River Wye. Deposition and erosion features surveyed in the field from 124 different locations were used to classify channel reaches as erosion, transport or deposition dominated. The underlying theory tested is that the dominant process (erosion or deposition) is determined by both the local and the upstream stream power, the latter being an indicator of the river's ability to provide sediment. The argument is that deposition is likely to be dominant when local stream power is notably lower than upstream and conversely for erosion. Meaningful patterns between the stream power attributes and the field-based channel classification were found using the method. Combining local and upstream stream power information uniquely arranged reaches into 4 classes of different sensitivity to erosion and deposition.

2.3.2 Data sets

The method requires the following data sets:

- flow discharge at monitored stations for calculating QMED (Centre for Ecology and Hydrology, open data)

- river network maps, could be taken from OS Open Rivers (Ordnance Survey, open data) or digital river network (Centre for Ecology and Hydrology, licensed data) Shapefile
- 50 m resolution DEM, could use the integrated height model 2m resolution digital terrain model (Environment Agency, licensed data) and resample to a 50 m resolution
- field observations provided by River Habitat Survey data (Environment Agency, open data)

2.3.3 Overview of method

The main steps in applying the method are as follows:

- QMED used as the reference discharge. Power regressions established between QMED and Shreve's (1966) index of river link magnitude (M) as suggested by Knighton (1999). Takes into account the non-linear relations between flow and distance downstream.
- Channel gradient obtained from a DEM using the altitude difference between a cell and a cell 4 km upstream.
- Bankfull width estimated using the empirical relation of Hey and Thorne (1986), as suggested by Knighton (1999).
- Values of QMED, gradient and width associated with each 50 m DEM cell along the river course.
- Local total and specific stream power defined as averages of the 10 stream power values, one for each 50 m of the DEM with the 500 m RHS reach.
- Upstream total and specific stream power values defined as the average over a specified upstream length of channel.
- The difference in total and specific stream power defined as local minus upstream stream power.
- Expert judgment used to classify the study reaches into laterally confined and unconfined channels, on the basis of bed and bank material (RHS), valley setting and the extent of the flood plain.
- The occurrence of deposition and erosion features are defined as either extended or limited.
- In total, 2 classes of confined and 4 classes of unconfined channel were defined on the basis of different configurations of deposition and erosion features.
- The results show that there are significant relationships between the channel classes and stream power profiles. A total stream power of 1,648 W/m^2 and a specific stream power of 34 W/m^2 emerge as the minimum energy necessary to trigger erosion processes, that is to mobilise sediment and to activate bank erosion and lateral channel migration. In a situation of a sediment supply deficit, this energy condition can trigger incision of the river bed. Reaches with specific stream power or total stream power lower than these thresholds tend to be stable and have limited ability to activate these geomorphic processes.

2.3.4 Outputs

Reaches are classified into 6 channel classes, according to unique combinations of predictors (channel confinement, specific and total stream power, and difference between local and upstream specific and total stream power). These relationships are formalised using a classification tree: confined, stable equilibrium; confined, deposition dominated; unconfined, stable equilibrium; unconfined, deposition dominated; unconfined, erosion dominated; unconfined, unstable equilibrium.

For confined channels, deposition dominated and equilibrium classes are separated by a threshold value in the difference between local and upstream specific stream power (with the upstream stream power averaged over 3 km).

For unconfined channels, deposition dominated and unstable equilibrium classes are separated from stable equilibrium and erosion dominated classes by a threshold value in the difference between local and upstream total stream power.

The different classes are associated with potential river channel sensitivity to change/response, where further investigation is warranted.

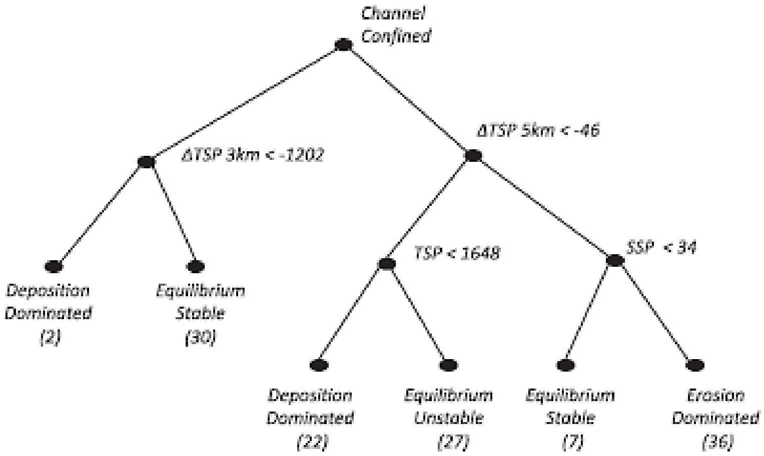


Figure 2-3 Example output from the map-derived stream power method, reproduced from Bizzi and Lerner (2015)

2.3.5 Strengths

- Uses relatively simple techniques and few resources, as well as readily available data sets. Method recognises that an applied tool should need little data to be practically applied.
- Provides a quantitative measure of the relative scale of channel instability between reaches.
- Provides a science-based approach for examining local sediment problems and the risks associated with different options for sediment management within the wider context of the catchment.
- Method could provide a broad understanding of catchment-scale sediment transfer systems nationally. At present, there is no means of considering sediment dynamics at the catchment scale due to data and operational constraints.

2.3.6 Weaknesses

- There is some uncertainty in the measurement of parameters used to calculate stream power for points across a catchment network (Bizzi and Lerner, 2013).
- Uses RHS data which is not a proper geomorphological assessment (Newson and others, 1998).
- The method relies on expert judgment to classify the study reaches into laterally confined and unconfined channels, on the basis of bed and bank material (RHS), valley setting and the extent of the flood plain.
- The method used to estimate the QMED values for points across the catchment is based on an empirical relationship and will not account for local variability.
- Bankfull width is based on a downstream hydraulic geometry relationship (Hey and Thorne, 1986) and therefore changes in width associated with local controls and variability, which might lead to significant differences in sediment transport, are not accounted for.
- There is uncertainty around data quality and processing.
- Simplifications within the model include the following assumptions: that the rate of sediment transport out of a reach is directly related to its specific stream power; that the supply of sediment into a reach is directly related to the stream power of its upstream neighbour(s); that the model represents a snapshot of a system that in reality evolves over time and is influenced by feedback; and that the model represents the watercourse as reach-based when in reality the channel varies continuously across space.
- The method's reach-based nature means that its outputs are sensitive to the reach boundaries that are identified. As a result, the method is limited in terms of its consistency.
- The method relies on identifying thresholds to distinguish between erosion or deposition dominated reaches. These will be different for each catchment, with results/trends potentially highly sensitive to the threshold set.
- The method does not include sediment 'source' explicitly, rather it makes a comparison between sediment transporting 'capacity' at a location with sediment transporting 'capacity' in the neighbouring upstream reach. In addition, the model only considers sediment sourced from the channel bed. No account is made for sediment derived from bank erosion, catchment run-off or colluvial inputs.

2.4 Method 3: REAS (Soar and others, 2017)

2.4.1 Overview

Soar and others (2017) examined the feasibility of a basin-scale scheme for characterising and quantifying river reaches in terms of their geomorphological stability status and potential for morphological adjustment based on auditing stream energy. A River Energy Audit Scheme (REAS) was developed, which involved integrating stream power with flow duration to investigate the downstream distribution of annual geomorphic energy (AGE). This measure represents the average annual energy available with which to perform geomorphological work in reshaping the channel boundary. Changes in AGE between successive reaches might indicate whether adjustments are likely to be led by erosion or deposition at the channel perimeter. A case study of the River Kent in Cumbria, UK, demonstrated that the basin-wide application of REAS is achievable without excessive fieldwork and data processing.

2.4.2 Data sets

The method requires the following data sets:

- digital elevation model of entire catchment to derive channel cross section width and depth and channel slope, for example, integrated height model 2 m resolution digital terrain model (Environment Agency, licensed data)
- flow duration curve, that is flow discharges at monitored stations (Centre for Ecology and Hydrology, open data)
- bed material particle size or size distribution from field survey or from existing, local sediment models
- channel and flood plain roughness coefficients from field survey or sourced from existing, local sediment or hydraulic models

2.4.3 Overview of method

The main steps in applying the method are as follows:

- Excess stream power is derived initially as an integrated measure accounting for the particle size distribution of bed material, which is then scaled up to the channel width to provide a bulk measure of stream energy within the cross section. Finally, this is integrated across the range of all sediment transporting flows according to how often they happen, thereby yielding a measure of annual geomorphic energy (AGE).
- Reach boundaries within the river network are delineated using the global zonation scheme of Gill (1970). This is a routine to aggregate reaches; it breaks a sequence of values into zones. Within each zone values are similar; and values differ from adjacent zones.
- Once reaches have been identified, REAS calculates a series of balances or differentials in AGE for each reach.
- The sequences of energy balances may be interpreted as trends in potential river channel sensitivity to change/response, where large absolute values may reveal areas of concern where further investigation is warranted.

2.4.4 Outputs

Reaches are classified into 3 channel classes, based on balances (differentials) in annual geomorphic energy. The AGE balance (differential) classes are:

- balance (indicative of stability or equilibrium in sediment transfer)
- negative (indicative of the potential for erosional processes)
- positive (indicative of the potential for depositional processes)

The sequences of energy balances may be interpreted as trends in potential river channel sensitivity to change/response, where large absolute values may reveal areas of concern where further investigation is warranted.

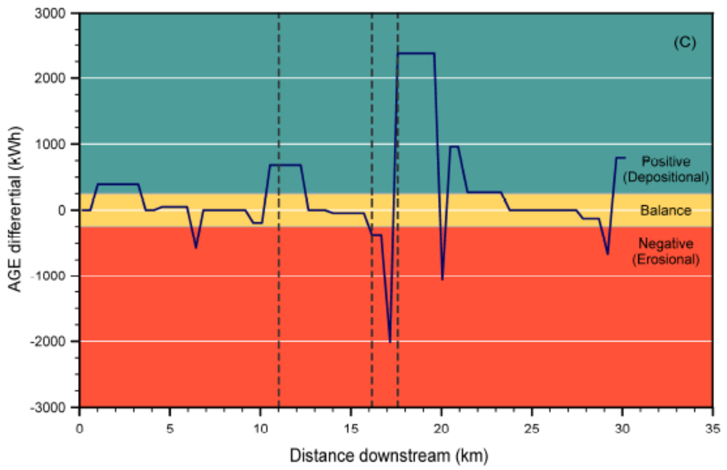


Figure 2-4 Example output from REAS, reproduced from Soar and others, 2017

2.4.5 Strengths

- Takes into account the full spectrum of sediment transporting flows based on gauging records rather than a single reference discharge.
- Provides a quantitative measure of the relative scale of channel instability between reaches.
- Uses relatively simple techniques and few resources, as well as readily available data sets.

2.4.6 Weaknesses

- The model is only coded in 'development' form and further coding might be needed for further application.
- The approach is more demanding on data than ST:REAM, using sediment size, roughness, cross sections and flow duration data, although indicative information on sediment calibre, roughness and channel depth will be enough for practical application.
- Stream power calculations in general do not take into account sensitivity of the channel boundary to change, sediment supply limitations, structures that disrupt continuity beyond the local scale, channel evolution and recovery in response to recent or historical influences and non-channel sediment inputs related to bank erosion, planform change and run-off.
- Sources of uncertainty include those related to data quality and processing, that is measurement of channel dimensions and estimation of variables such as discharge or sediment size, as these are often not measured locally.
- One of the greatest sources of uncertainty is identifying unique reaches of similar energy for calculating the differentials in AGE.
- It is not straightforward to choose a threshold that demarcates geomorphologically stable reaches.
- Presence of bedrock could yield misleading results and would need to be identified with site visits or a suitable data source, such as fluvial audit data or aerial imagery.

- Will not identify hotspots of channel instability at the local, intra-reach scale.
- It uses the principle that an imbalance in annual geomorphic energy creates increased risk, but this may not happen in reality – for example the model may predict that a reach has an excess of energy compared with surrounding reaches and that erosion will occur; but the reach in question may harmlessly dissipate the excess energy through processes of natural, gradual channel changes that pose no risk in terms of channel adjustment or flooding.

2.5 Method 4: CAESAR-Lisflood (Coulthard and others, 2013)

2.5.1 Overview

Landscape evolution models (LEMs) simulate the geomorphic development of river basins over large timescales and areas. As a result, they have been developed with simple steady flow models that allow long time steps, but not shorter hydrodynamic effects (the passage of a flood wave) to be modelled. Non-steady flow models that incorporate these hydrodynamic effects tend to need far shorter time steps (seconds) and use more expensive numerical solutions preventing them from being included in LEMs. The LISFLOOD-FP simplified 2D flow model addressed this issue by solving a reduced form of the shallow water equations using a very simple numerical scheme. The LEM CAESAR and hydrodynamic LISFLOOD-FP were merged to create the CAESAR-Lisflood model, and through a series of tests showed that using a hydrodynamic model to route flow in an LEM has many advantages.

2.5.2 Data sets

The method requires the following data sets for modelling in basin mode:

- DEM of entire catchment - resolution depends on the area (km^2) modelled, but commonly ranges from 10 m to 50 m, although coarser and finer resolutions are possible.
- Hourly rainfall record for region - length of record depends on available data sets and required model run time, but typically spans decades for many studies, overlapping time period with river flow gauge data is necessary for model calibration.
- For scour and deposition modelling, the model needs a percentage input of each size, up to 10 different sizes. The minimum is one grain size, that is, D50, but including different grain sizes such as D90 allows natural armouring to occur in the channel. Adding more grain sizes (that is, 20% of size a, 30% of size b and 50% of size c), allows sorting, but with additional grain diameters comes increased model run times. Ideally, this data would come from river bed material sampling, but could be estimated from river type or from known grain size distributions in donor catchments with similar characteristics.
- Manning's n for DEM grid cells - one uniform value can be chosen or values can be entered based on known surface cover and/or from hydraulic models that may exist for the chosen catchment.
- Hourly flow record from flow gauges within the catchment for model calibration - length of record depends on available data sets and required model run time, typically decades for many studies. An overlapping time period with rainfall

gauge data is necessary for model calibration. A flow gauge located at the catchment outlet is necessary for calibration over the entire model extent.

2.5.3 Overview of method

The main steps in applying the method are as follows:

- CAESAR-Lisflood can operate with 3 different drivers (a) lumped or spatially distributed rainfall, (b) point discharge data (for example, at a point stage height or discharge inputs), (c) tidal inputs. These can operate individually or together.
- The hydrological model features a distributed version of TOPMODEL and within user defined areas can have different rainfall inputs (for example, different cells from rain radar or polygons representing rain gauge areas) as well as different land use covers (for example, forested, grassland, urban).
- Run-off generated via the hydrological model or directly inputted discharges are then routed using the Lisflood-FP scheme (Bates and others, 2010). This scheme calculates flow discharges according to the water surface slopes and roughness; from this water depths are resolved. The model is 2-dimensional and hydrodynamic, has been thoroughly tested and is applied throughout the world for flood risk modelling.
- Flow depths and velocities determined by the hydraulic model are then used to calculate a shear stress that is fed into a sediment transport function to model fluvial erosion and deposition. CAESAR-Lisflood provides a choice of sediment transport function with the Einstein (1950) Meyer-Peter-Muller (1960) and the Wilcock and Crowe (2003) method.
- Sediment transport is then determined for up to 9 different grain size classes and these may be transported as bedload or suspended load. A distinction is made between the deposition of bed load and suspended load, where bedload is moved directly from cell to cell, whereas fall velocities and the concentration of sediment within a cell determine suspended load deposition.
- Incorporating multiple grain sizes and formulating a model of the selective erosion, transport and deposition of the different sizes allows different sediment sizes to be modelled. Sub-surface sediment data is stored via a system of active layers made up of a surface active layer (the stream bed), multiple buried layers (strata) and, if needed, an unerodible bedrock layer (Van de Wiel and others, 2007).
- Lateral erosion is also simulated, which is driven by the channel curvature and rates of near bend erosion (Van de Wiel and others*,* 2007).

2.5.4 Outputs

The model outputs elevation and sediment distributions through space and time, as well as discharges and sediment fluxes at the outlet(s) through time.

Additional fluxes at specified points in the catchment or reach can be easily obtained. These can be used to examine processes of erosion and deposition through the catchment and river network.

Figure 2-5 Example output from CAESAR-Lisflood, reproduced from Van De Wiel and others, 2007.

2.5.5 Strengths

- Has been used in over 60 peer-reviewed studies across the world (Skinner and Coulthard, 2017).
- Provides a science-based, analytical approach for examining local sediment problems and the risks associated with different options for managing sediment, within the wider context of the catchment.
- Considers non-channel sediment inputs from the catchment, valley sides, bank erosion.
- Selective erosion, transport and deposition of different size grain fractions allows different sediment sizes to be modelled.
- In gauged catchments, it is possible to use the gauge data to calibrate the hydrology. This enables the model to be tested and calibrated.

2.5.6 Weaknesses

- Applying the method is relatively complicated for someone with no modelling experience, but this could be overcome through specific user-training courses, someone senior overseeing the process and through quality assurance.
- Requires a great deal of calculations. Would require specific IT infrastructure, such as cloud computing, to be established to apply the method nationally.
- A bedrock layer needs to be defined, which includes unerodable areas, such as hard in-channel structures (for example, weirs) and bank protection. If these unerodable areas are not defined, the model is likely to overpredict erosion and produce unrealistic patterns of erosion and deposition.
- As the model predicts landscape change, bank vegetation and material characteristics not being accounted for in the model may result in overpredicting lateral activity, due to the stability that they provide to the river banks.
- The method relies on the accuracy of the DTM to represent current topography and artificial structures. For example, a realigned channel may not be well represented in the DTM, causing flow to follow the natural channel route. Therefore, without local knowledge the results may be misleading.

2.6 Method 5: Half-yield method (Dr Philip Soar, University of Portsmouth)

2.6.1 Overview

The method was designed to be simple and suitable to use at the catchment scale for alluvial channels, based on much of the literature reviewed in report 1 (FRS17183/R1) related to sediment transport and channel stability. It is based on readily available data sets where possible/practical and with fully justifiable assumptions. The method does not require a backwater model or reach delineation and, in treating sites independent of other locations or reaches in the river system, it represents a credible alternative work flow to existing accounting methods based on balances in sediment transport between contiguous reaches.

2.6.2 Data sets

The method requires the following data sets:

- integrated height model 2 m resolution digital terrain model (Environment Agency, licensed data)
- channel width and depth – taken from River Habitat Survey (Centre for Ecology and Hydrology, open data via the Environment Agency)
- channel slope – taken from the digital river network data set (Environment Agency, licensed data)
- sediment size – taken from River Habitat Survey (Centre for Ecology and Hydrology, open data via the Environment Agency)
- discharge – flow duration curve from nearest river gauge (Centre for Ecology and Hydrology, open data)

- roughness – constant roughness value of 0.04 assumed for trial - could possibly generate Manning n values for channel and flood plain based on the catchment estimation system or have representative values for different channel types

2.6.3 Overview of method

The proposed method comprises 2 stages of assessment:

- channel performance (*P*) - The sediment transport capacity of the subject channel is compared with the sediment transport capacity of a theoretical regime channel, according to a capacity-regime transport ratio. A suitable performance tolerance band could be used to identify stable channel reaches where sensitivity to change is not significant
- channel effectiveness (*E*) - channel 'effectiveness' here, differentiates between the geomorphological performance of in-channel flows and bank overtopping flows and therefore provides an indication of the significance of flood flows on the long-term sediment yield. This is achieved by analysing the cumulative sediment yield (decimal contribution to the long-term sediment budget).

2.6.4 Outputs

The performance factor identifies if the location is dominated by erosional or depositional behaviour, or generally stable. The effectiveness index indicates whether flood flows or in-channel flows are most geomorphologically effective, or if there is a balance between the two for transporting sediment.

The output is provided in a CSV file and can be imported into ArcGIS to create a shapefile that can be displayed at the location of the data point (Figure 2-6).

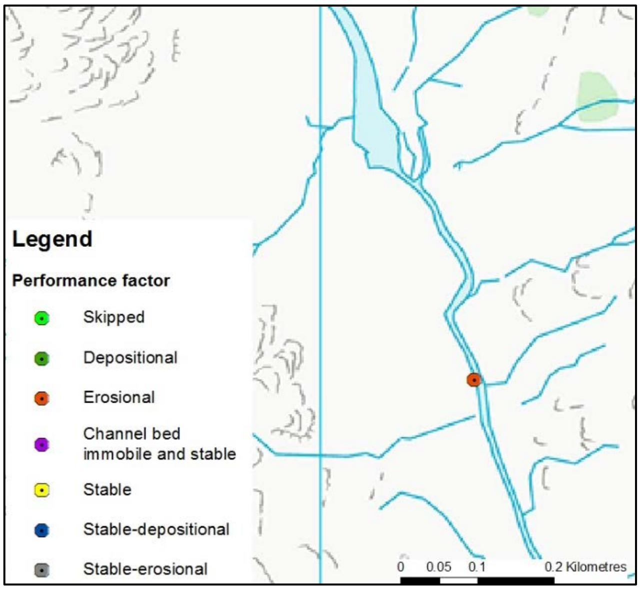


Figure 2-6 Example output from the half yield method in ArcGIS. The example point is classified as erosional in terms of the performance factor (P = -2.2) and effectiveness index (E = -1).

2.6.5 Strengths

- Conceptually, the underlying science and logic is sound and backed up by published research.
- Each site (cross section) is treated independently. Linking cross sections in a network system is not required. Locations are not required to be regularly spaced along the river network, instead the method is applied where data is available or at a site of particular interest, such as a site selected for development, engineering or restoration. In this context, the method would nest conformably within a fluvial audit that placed the site correctly in its 'catchment context'.
- Overcomes some of the limitations/assumptions of comparative accounting system methods (such as ST:REAM).
- Reach delineation is not required.
- A stream power threshold is not required for classifying unstable locations.
- The method differs from others in that channel morphology (in its sediment transporting efficiency) is compared with the hypothetical equilibrium morphology in terms of sediment continuity. The method therefore, lends itself to evaluating the sensitivity of a site's transporting 'efficiency' in driving or responding to changes in channel geometry (width, depth), with and without climate change. From a management perspective, the method has the potential to highlight which managed reaches could be returned to an equilibrium state.
- Relatively simple method, apart from the delineation of the catchment boundaries for generating the FDCs, which requires training from a GIS specialist in order to carry this out successfully.

2.6.6 Weaknesses

- The method has not previously been tested or coded.
- Any site in a fluvial (alluvial) system can only operate independently of other locations in that system over short timescales. Therefore, the half yield method indicates current dynamic stability or evolutionary trend, and initial process-response to climate change.
- The method relies heavily on the location, availability and accuracy of RHS data. For example, where no RHS survey data is available there would be large gaps within the coverage of the method outputs. Possible lack of available RHS data points could therefore lead to long reaches with no method output, potentially missing reach scale processes.
- The method relies on the completeness of the DRN data.
- Slope is held constant in the model, therefore ‘stable’ refers to equilibrium sediment transport at the governing slope. The derived regime cross sections assume existing slope values. A limitation of the approach is its inability to suggest likely morphological adjustments on the basis of gradient and planform. An improvement might be to derive a suite of outputs at each location of interest for a set of river slopes to to reflect example planforms.
- Method does not account for net erosion or deposition rate which asset managers need. Lateral instability is also not accounted for.

2.7 Method 6: Shear stress data mining method (Dr Barry Hankin, JBA Consulting)

2.7.1 Overview

This approach makes use of existing large scale, high resolution national flood mapping data sets. There is considerable depth and velocity information available, with national coverage for a range of probability events. As far as we know, information to understand shear stresses and likely sediment risk has not been gathered on a national scale.

The approach relies on an efficient ArcGIS model builder code that computes local effective shear stress based on average velocity, depth and roughness. This is compared with critical shear stress for entrainment and erosion, using 3 assumptions on deposition, erosion and sediment grain size distribution. It results in a zonal classification of sediment erosion, transition and deposition based on comparing local effective shear stress and critical shear stress. The science underpinning this method is based on the physics of fluid flow and critical shear stress for entrainment and deposition.

2.7.2 Data sets

The method requires the following data sets:

- national DTM, for example, integrated height model 2 m resolution digital terrain model (Environment Agency, licensed data)
- risk of flooding from surface water complex model outputs (Environment Agency, open data) – continuous rasters of depths and velocities
- landcover – Land Cover Map 2007 (Centre for Ecology and Hydrology licensed data) or CORINE Land Cover Map 2012 (Centre for Ecology and Hydrology, open data) with a landcover/roughness assumption
- assumption on D50 grain size (where the D50 is the median diameter of the particle size distribution). Alternatively, the model could be run multiple times with different values and the user could look up the correct value once known. Could also be sourced from existing, local sediment models.
- It would be possible to obtain national fluvial flood modelling depth and velocity grids commercially to improve the maps.

2.7.3 Overview of method

The main steps in applying the method are as follows:

Effective shear stress can be derived using a quadratic expression which gives desirable properties for shear in relation to depth and depth averaged velocity (Bates and others, 2005). This quadratic equation can then be used and compared against critical shear stress to identify where erosion is more likely.

Areas where the calculated shear stress is greater than the critical shear stress are classified as erosional. A model parameter ‘deposition threshold’ is then applied, which is a user-defined ratio defining the critical shear stress for deposition as a factor of critical shear stress. Areas where the calculated shear is less than this threshold are classified as depositional. If this parameter is set too high, deposition will occur wherever there is no erosion, and if too low there will hardly be any deposition shown.

Manning's coefficient can be estimated based on landcover – for instance using a look-up table between different covers and Manning's and a national raster of Manning's using CORINE derived. It is important to note that there will be limitations associated with this method, since not all riparian roughness would be represented in national land cover data sets.

2.7.4 Outputs

The model outputs a zonal classification of sediment erosion, transition and deposition as a raster GIS file format. An example is shown in Figure 2-7. The zones are produced for an example 3.33 % annual exceedance probability (AEP) surface water simulation, assuming a D50 of 50 mm.

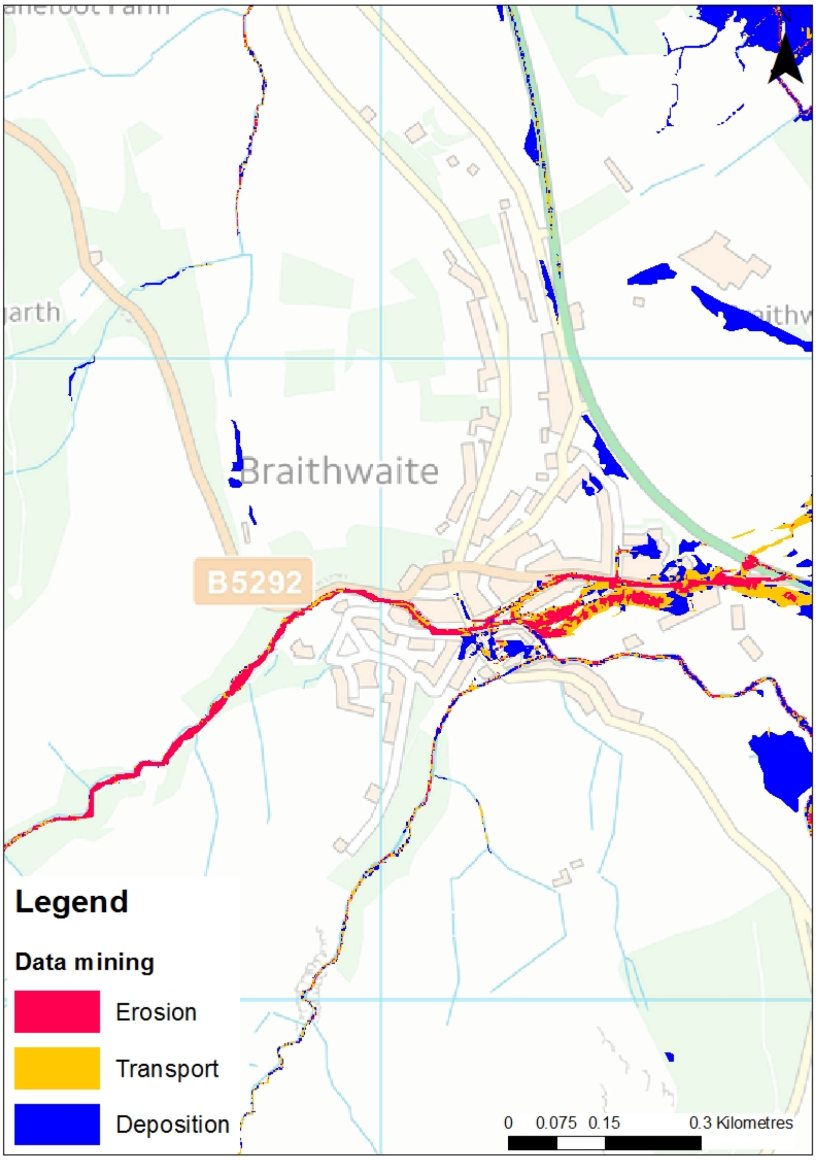


Figure 2-7 Risk map produced at Braithwaite, Cumbria, site of considerable sediment movement and subsequent flood risk during the 2015 floods

2.7.5 Strengths

- National data set not previously explored - rich data set at 2 m resolution.
- Multiple return periods/AEPs: 3.33% 1% and 0.1% AEP.
- Easy to apply. A single national run of the above code was tested and it takes 12 hours, so multiple scenarios and, for example, D50 grain sizes can be run to use when local sediments are known.
- The model builder code is easy to adapt and has been used experimentally on small catchments and on a national 2 m grid.
- Minimal training required.
- Provides a quantitative measure of the potential for erosion, deposition and transport of sediment.
- Can provide a broad understanding of catchment-scale sediment transfer systems nationally.

2.7.6 Weaknesses

- Requires either national estimates of grain size distribution or a series of D50s to be run and the user to choose the right zonation given local knowledge. A library would be produced so users can select the most appropriate.
- Geomorphological flows for large fluvial systems are not for whole catchment flows. The risk of flooding from surface water map only uses $5m^2$ tiles so the technique may only be useful in headwaters, but this is perhaps where activity is more significant. There is a WFD waterbody catchment layer available that identifies which catchments are headwaters nationally, which could be used to mask areas where the method is applicable.

2.8 Summary

An overview of the 6 methods added to a longlist for potential testing in the trial phase is presented in Table 2.1.

These methods were assessed based on their potential to be applied on a national scale, their strengths and weaknesses, along with consideration of whether climate change is (or could be) factored into the method. An overview of appropriate data sources that predict the impact of climate change on river flows is presented in section 7.

Table 2.1 Methods longlisted for the trial phase

Method	Overview	Main strengths/ limitations	Ability to incorporate climate change
ST:REAM	ST:REAM is a stream power method that is applied to a river system on a reach by reach basis. The method compares the quantity of sediment input to a reach (supply) and the quantity that can be transferred downstream (capacity). If	**Strengths:** The method uses relatively simple techniques and few resources, as well as readily available, national data sets. ST:REAM recognises that an applied tool needs few	Cannot be incorporated easily.

Method	Overview	Main strengths/ limitations	Ability to incorporate climate change
	supply exceeds capacity, the reach is likely to be dominated by depositional processes. If capacity exceeds supply, the reach is likely to be dominated by erosional processes. ST:REAM was designed to be a simple method of predicting system-wide trends in geomorphic processes. The method was automatically taken forward to the trial phase of the project.	data requirements to be practically applied. The method is fully coded with a user guide. **Limitations:** No account is made for sediment sources other than the channel bed, including bank erosion, delivery from catchment run-off or colluvial inputs.	
Map-derived stream power	The method is a stream power method that is applied to a river system on a reach by reach basis. The dominant geomorphic process (that is, erosion, deposition or stable) is determined by both the local and upstream stream power, the latter being an indicator of the river's ability to supply sediment. Reaches are classified into 6 channel classes according to unique combinations of predictors, including channel confinement and stream power. The method uses map-derived and remotely sensed data, as well as River Habitat Survey data and river gauge data. The method was longlisted because it appeared to be a promising stream power based methodology worth considering for these trials.	**Strengths:** The method uses relatively simple techniques and few project resources, as well as readily available, national data sets. The method recognises that an applied tool needs few data requirements to be practically applied. **Limitations:** No account is made for sediment sources other than the channel bed, including bank erosion, delivery from catchment run-off or colluvial inputs.	Climate change can be incorporated by scaling QMED. However, climate change representations are typically applied to higher return period flows and therefore applying a climate change factor to QMED would be ineffectual.
REAS	REAS is a stream power method that is applied to a river system on a reach by reach basis. The method calculates the average annual energy available with which to perform geomorphological work in reshaping the channel boundary. Changes in this energy between successive reaches is used to indicate whether adjustments are likely to be led by erosion or deposition at the channel perimeter. The method used remotely sensed data, river gauge data and field survey data.	**Strengths:** Takes into account the full spectrum of sediment transporting flows based on gauging records rather than a single reference discharge. **Limitations:** The approach is more demanding on data than ST:REAM, using sediment size, roughness, cross sections and flow duration data, although indicative information on sediment calibre, roughness and channel depth will be	Climate change influences could be incorporated by manipulating the input flow data using Future Flows (Centre for Ecology and Hydrology).

Method	Overview	Main strengths/ limitations	Ability to incorporate climate change
	The method was longlisted because it appeared to be a promising stream power based methodology worth considering for these trials.	enough for practical application. The model is only coded in 'development' form and further coding might be required for further application.	
CAESAR-Lisflood	CAESAR-Lisflood is a type of landscape evolution model that combines a time-varying flow model (Lisflood-FP) with a geomorphic model (CAESAR) to simulate erosion and deposition in river catchments and reaches over time scales from hours to thousands of years. The model outputs elevation and sediment distributions through space and time, as well as discharges and sediment fluxes. This method was longlisted because it is capable of providing net rates of erosion and deposition.	**Strengths:** Considers non-channel sediment inputs from the catchment, valley sides and bank erosion. Provides a science-based, analytical approach for examining local sediment problems within the wider context of the catchment. **Limitations:** Requires many calculations and would require specific IT infrastructure, such as cloud computing, to be established for national-scale application.	Climate change can be incorporated by adjusting the rainfall inputs to CAESAR-Lisflood.
Half-yield method	The half-yield method compares the sediment transport capacity of the channel at a test location with the sediment transport capacity of a theoretical regime channel. The method assumes that the dimensions of the theoretical bankfull channel are adjusted to the half-load discharge, which is the discharge associated with 50% of the cumulative sediment load. Comparing the sediment transport capacity of the ‘real’ channel and the ‘regime’ channel enables the likely stability of the channel at the test location to be assessed. A large difference indicates that erosional or depositional processes are likely to be occur because the channel is not adjusted to the sediment transport regime. A small difference indicates that the channel dimensions are relatively well adjusted to the prevailing sediment transport regime.	**Strengths:** Linking cross sections in a network system is not required. Overcomes some of the limitations/assumptions of comparative accounting system methods such as ST:REAM, Bizzi and Lerner’s (2015) map-derived stream power method and REAS. **Limitations:** The method relies heavily on the location, availability and accuracy of RHS data.	Climate change influences could be incorporated by manipulating the input flow data using future flows (Centre for Ecology and Hydrology).

Method	Overview	Main strengths/ limitations	Ability to incorporate climate change
	This method was longlisted because it differs from the other methods and because it has the potential to highlight which managed reaches could be returned to an equilibrium state.		
Shear stress data mining method	The approach uses the risk of flooding from surface water complex model outputs (depth and velocities) to calculate local shear stress based on average velocity, depth and roughness. This is compared with critical shear stress for entrainment and erosion, using 3 assumptions on deposition, erosion and sediment grain size distribution. The method outputs a zonal classification of sediment erosion, transition and deposition based on a comparison of local shear stress and critical shear stress. This method was longlisted because it uses a data rich, high resolution, national-scale data set.	**Strengths:** Uses a 2 m resolution national data set, not previously explored. Method is fast and easy to apply. **Limitations:** Geomorphological flows for large fluvial systems are not for whole catchment flows – the risk of flooding from surface water map only uses 5 km^2 tiles, and flood flows are not routed from one tile to the next, which means that flows do not accumulate in the lower areas of large river systems that span over many tiles.	Cannot be incorporated directly, as the underlying data is only available for 3 annual exceedance probabilities (3.33%, 1% and 0.1%). However, changing from the 3.33% to the 1% will give an estimate of the sensitivity of spatial distribution or erosion and deposition potential to increased rainfall involved.

3 Method and catchment selection

3.1 Method selection

Following a literature review, 6 methods were longlisted as potentially suitable for producing national scale information on river hydraulics and behaviour, as outlined in section 2. This section outlines the shortlisting process carried out to select 4 methods to take forward to the trial phase of the project.

3.1.1 Multi-criteria and shortlist

A multi-criteria analysis was carried out (Appendix B) to further test the feasibility of using the methods outlined in this report to produce national-scale information on river hydraulics and behaviour and to help shortlist methods taken forward to the trial phase of the project. The methods were scored, ranking them according to quality criteria shown in Table 3.1.

Table 3.1 Method quality scoring criteria

Quality criteria	Scoring criteria	Criteria weight
Suitable approach (total 45%)	How accepted is the method? (1 = not very, 10 = very)	10
	Level of input data required (1 = high, 10 = low)	10
	Complexity of method (1 = high, 10 = low)	5
	Ability to provide geomorphology baseline (1 = low, 10 = high)	10
	Ability to include climate change (1 = challenging, 10 = simple)	10
Scalability (total 25%)	Ability to create national coverage data (1 = challenging, 10 = simple)	15
	Consistency in application (1 = low, 10 = high)	5
	Expertise required to apply method (1 = high, 10 = low)	5
Outputs (total 30%)	Quality of outputs (1 = low/simple, 10 = high/complex)	10
	Use as a management planning tool (1 = low, 10 = high)	5
	Ability to identify benefits for asset managers (1 = low, 10 = high)	10
	Interpretation needed (1 = low, 10 = high)	5

3.1.2 Methods taken forward to the trial phase

The 4 highest scoring methods were taken forward to the trial phase of the project:

i. CAESAR-Lisflood

ii. ST:REAM

iii. Half-yield

iv. Shear stress data mining

3.2 Catchment selection

A longlist of catchments in England and Wales was initially selected based on the availability of fluvial audit data sets and suggestions from the project steering group of catchments that have been heavily studied and researched. The longlist was separated into 3 environmental settings (upland, lowland and upland-lowland transitional) to ensure each environment was represented within the trial catchments.

3.2.1 Multi-criteria analysis and shortlist

A multi-criteria analysis (MCA) was carried out, providing a score of 0-3 for each of the following criteria:

- morphological activity (3 = very active, 0 = no known geomorphological activity)
- fluvial audit availability (3 = multiple audits, 0 = no availability)
- other known data/reports (3 = numerous information or extensive knowledge, 0 = no additional information available)
- heavily studied by academics (3 = many known studies, 0 = no known studies)
- previous modelling studies (3 = good hydraulic modelling data available, 0 = no known modelling data)
- River Habitat Survey (RHS) data sets (scoring 3-0 based on the total number of surveys available and date of last survey)
- availability of 1 m LiDAR (2017) data (3 = >70% catchment coverage, 0 = 0% coverage)
- availability of all surveyed LiDAR data (3 = >70% catchment coverage, 0 = 0% coverage)
- availability of aerial imagery (3 = > 60% catchment coverage, 0 = 0% coverage)

The project steering group was invited to provide information and knowledge of each of the catchments and the availability of data, which was incorporated within the MCA. The highest scoring 3 catchments were then selected from the remaining catchments.

The final 3 catchments selected were the River Kent (Cumbria), the River Stour (Dorset) and the River Wharfe (North Yorkshire). These catchments provided a good representation of the 3 environmental settings stated above, allowing the trials to be carried out within catchments with different hydromorphological processes.

4 Method trials and results

4.1 Overview

A summary of the methods trialled in each of the catchments is presented in Table 4.1. To work effectively within the project contract and timescales, not all methods could be trialled in all catchments. ST:REAM and the half-yield method were applied in all 3 test catchments, whereas CAESAR-Lisflood, a more resource intensive method, was only applied in the River Kent catchment.

Table 4.1 Summary of methods tested in each catchment

Method	Kent	Stour	Wharfe
ST:REAM	✓	✓	✓
CAESAR-Lisflood	✓	×	×
Half-yield	✓	✓	✓
Shear stress data mining	✓	✓	✓

4.2 Methodology

The method approaches and step-by-step workflows of how to apply ST:REAM, CAESAR-Lisflood and half-yield methods are presented in Appendix C.

The shear stress data mining method was explored separately to the other 3 methods because it was new and untested, and due to its encouraging potential, shown in the multi-criteria analysis, as a model that is quick to run and can produce national coverage. A separate parallel study was carried out to better understand the method and carry out preliminary tests on existing results (2 example maps corresponding to the 3.33 % and 1% annual exceedance probability surface water maps, both assuming a D50 grain size of 50 mm, a Manning's roughness of 0.05, and a Shields constant of 0.6). The results are reported in Appendix D, with the parallel study described further in FRS17183/R4.

New results were produced using the work flows. These were validated at spot check locations against available fluvial audit data.

A number of points were selected in the 3 test catchments: 10 in the Kent catchment, and 8 in the Stour and Wharfe catchments.

Spot check locations were chosen based on the following criteria:

- where processes of erosion and deposition are known to operate
- where the watercourse is known to be relatively stable
- other random locations across the catchment

The results for the ST:REAM, CAESAR-Lisflood and half-yield methods in the River Kent are presented in the next section. Results for the Stour and Wharfe catchments are presented in Appendix D. The method and results from the shear stress data mining method are presented separately in Appendix D.

4.3 Results

4.3.1 River Kent (Cumbria)

The River Kent (Cumbria) originates in the hills surrounding Kentmere, passing through the town of Kendal, before flowing into the north of Morecambe Bay. It experienced flooding in 2005, 2009 and in winter 2015 to 2016.

Ten points were selected in the Kent catchment, with the results validation for the ST:REAM, CAESAR-Lisflood and half-yield methods presented below. Table 4.2 describes what each of the methods shows in the maps that follow to help interpret the results.

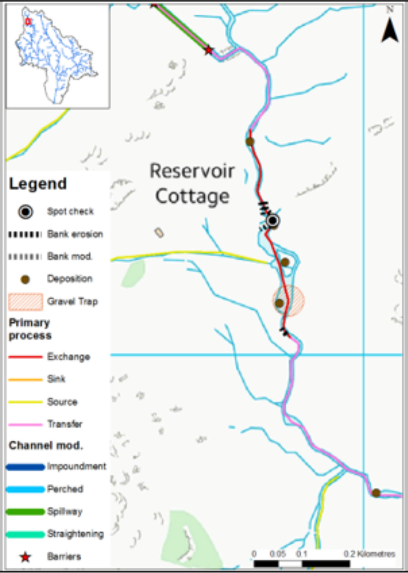
Table 4.2 Results maps description to help interpretation

Method and legend as shown on the results maps	Interpreting the results to understand dominant processes of deposition, transfer and erosion
Blue = deposition Grey = transfer Red = erosion	ST:REAM results are based on the value of the unit width stream power balance (calculated by dividing the unit width stream power of the reach in question by the reach immediately upstream). Threshold values of the unit width stream power balance are used to delineate dominant geomorphological processes for each reach. Threshold values 0.59 and 2.4 are based on research by Parker and others, 2015. Values less than 0.59 are classed as depositional (blue), values between 0.59 and 2.49 are classed as transfer (grey), and values greater than 2.49 are classed as erosional (red).
CAESAR-Lisflood Elevation diff. (m) -6.9 - -1.0 -1.0 - -0.5 -0.5 - -0.1 -0.1 - 0.1 0.1 - 0.5 0.5 - 1.0 1.0 - 5.0 Blue = deposition No colour = no significant change in bed elevation Red = erosion	CAESAR-Lisflood outputs data in the form of a raster grid of elevation differences (m), with negative values indicating deposition and positive values indicating erosion. Depositional values (blue) are negative in the output raster grid as they represent the surface elevation at the start of the simulation minus the surface elevation at the end of the simulation. Similarly, erosional values (red) are positive in the output raster grid as they represent the surface elevation at the start of the simulation minus the surface elevation at the end of the simulation. Areas without a significant change in bed elevation over the model simulation time are expected to illustrate reaches through which sediment is transported. These are identified by the 'no colour' areas in the CAESAR-Lisflood results.

Method and legend as shown on the results maps	Interpreting the results to understand dominant processes of deposition, transfer and erosion
Half-yield Performance factor Skipped Depositional Erosional Channel bed immobile and stable Stable Stable-depositional Stable-erosional	Half-yield method produces a performance factor and the effectiveness index. Both must be examined and compared to a matrix of possible outcomes to fully interpret the results accurately. In the performance factor, 'skipped' indicates that the River Habitat Survey data available was insufficient to calculate the half yield method. 'Depositional' indicates that depositional processes are dominant in the reach. 'Erosional' indicates that erosional processes are dominant in the reach. Reaches identified as 'stable' will be dominated by transfer processes. Reaches defined as 'channel bed immobile and stable' will act as a transfer for small sediment sizes. 'Channel bed immobile and stable' indicates that the sediment at the location is too large to define an alluvial regime channel that meets the half yield criterion. The channel will act as a transfer reach for small sediment sizes and potentially depositional for fines. 'Stable' indicates that the channel is stable in terms of sediment transport continuity and therefore represents a channel morphology which is 'in regime' (sensitivity to change is not significant). It also indicates that there is a balance in sediment yield between in-channel and overtopping flows. Sediment transport processes are dominant. 'Stable - depositional' indicates that in-channel discharges are responsible for performing most work in transporting sediment, and might indicate a channel that is too deep and/or wide for the imposed sediment transport regime. This is associated with gradual bed raising. 'Stable-erosional' indicates that overbank discharges are responsible for performing most work in transporting sediment and might indicate a channel that is too shallow and/or narrow for the imposed sediment transport regime. This is associated with gradual bed scour and possible deposition of fines.

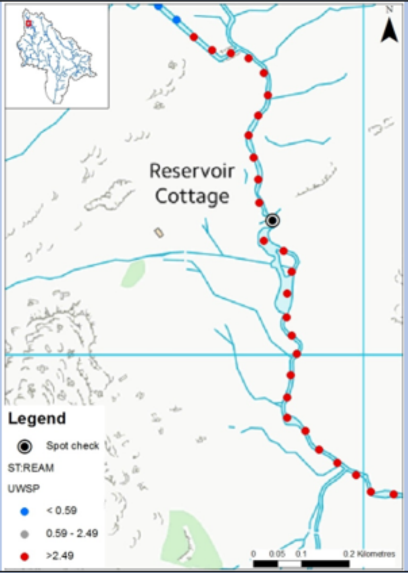
Reach: Kent_01, Watercourse: River Kent, OS NGR: 344809, 507281

Audit data



- The spot check location is downstream of the Kentmere reservoir, which acts to trap sediment from the headwaters, disrupting sediment continuity.
- Erosion of unstable quarry workings is occurring, as well as bed incision due to a historic dam failure.
- Degraded nature of reach soon lost because of significant sediment inputs from the former Jumb Quarry.
- Key process: Erosion

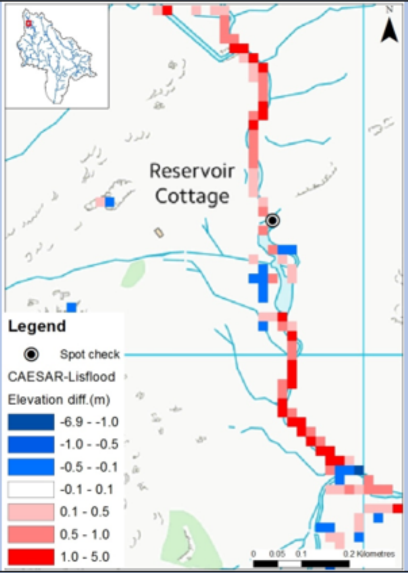
ST:REAM



In the **ST:REAM** model, the reach is classified as erosional.

This broadly agrees with the audit data.

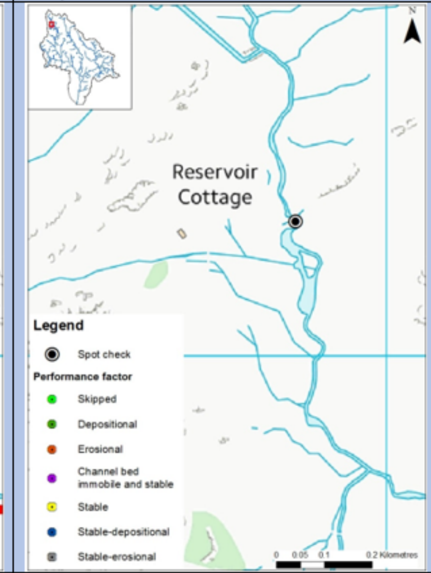
CAESAR-Lisflood



In the **CAESAR-Lisflood** model, the reach is classified as erosional, with small pockets of deposition

This broadly agrees with the audit data.

Half-yield



No RHS sample point available for this reach.

Conclusion:

- **Two out of three methods provide results which agree with the Fluvial Audit (ST:REAM and CAESAR-LISFLOOD).**
- **Both ST:REAM and CAESAR-LISFLOOD highlight erosional processes well, however the process of transfer (i.e. sections of the reach which do not display erosional characteristics) are not depicted well in the tested methods. This may give the end user an incorrect understanding of the process which could be misinterpreted.**
- **The Half-yield method could not be used due to the lack RHS data in the area.**

Figure 4-1 Results validation: Kent 01

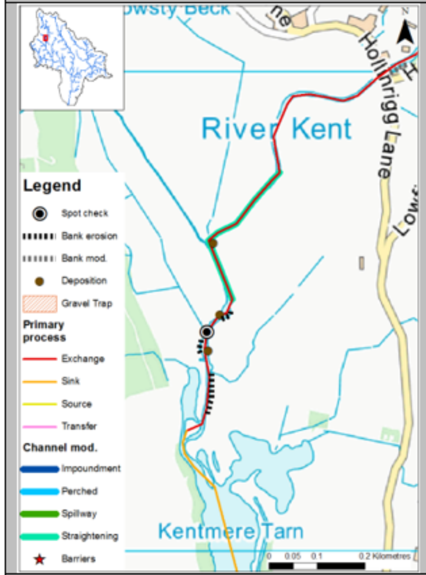
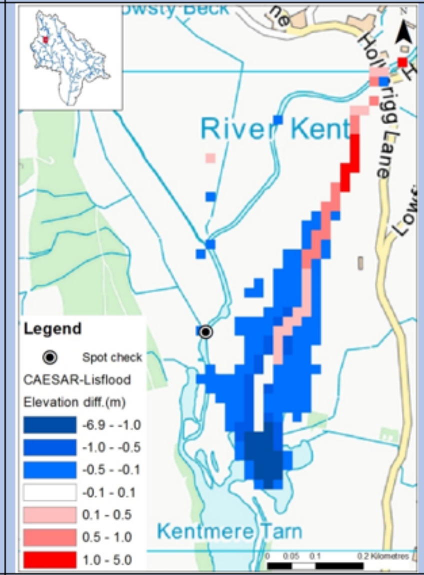
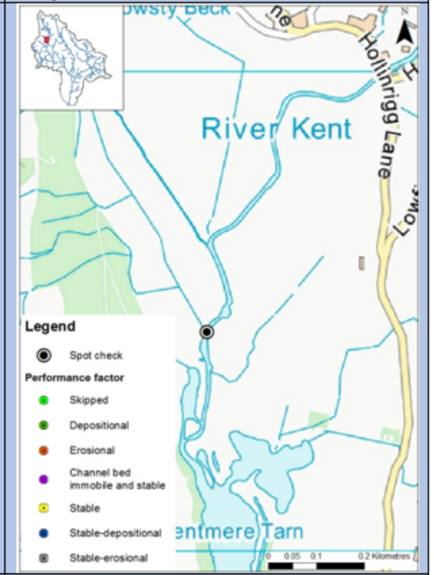
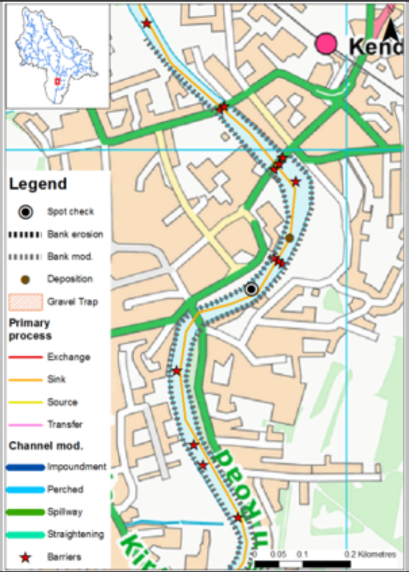
<table>
<tr><th colspan="4">Reach: Kent_02, Watercourse: River Kent, OS NGR: 345440, 503458</th></tr>
<tr><th>Audit data</th><th>ST:REAM</th><th>CAESAR-Lisflood</th><th>Half-yield</th></tr>
<tr>
<td>
</td>
<td>
</td>
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>
Kentmere Tarn is a significant sediment trap, and large active bar features are present upstream.
Channel attempting to wander across the floodplain by eroding banks.
Historic modification (straightening) upstream of the spot check location.
Key process(es): Erosion and deposition.</td>
<td>In the ST:REAM model, the reach is classified as depositional.</td>
<td>In the CAESAR-Lisflood model, the reach is classified as depositional, with small pockets of erosion.</td>
<td>No RHS sample point available for this reach.</td>
</tr>
<tr><td colspan="4">Conclusion:
Within this reach the most suitable method for broadly characterising the dominant reach scale process is ST:REAM.
The Half-yield method could not be used due to the lack RHS data in the area.
CAESAR-LISFLOOD broadly depicts the correct process; however, the channel is not shown to be in the correct location due to its perched nature and the coarse LIDAR used. As a result, this presents incorrect erosional processes.</td></tr>
</table>

Figure 4-2 Results validation: Kent 02

Reach: Kent_03, Watercourse: River Kent, OS NGR: 351801, 492711

Audit data

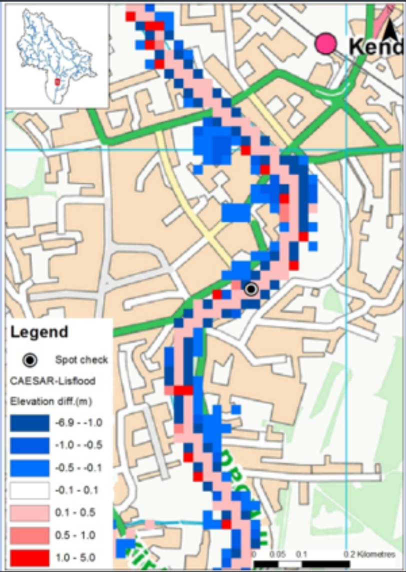


- The channel is confined, embanked, overwide and walled with no floodplain connectivity.
- As a result of the artificial channel environment, in particular the overwide nature of the channel alongside the numerous weirs and bridges, extensive deposition across the bed occurs.
- Characterised by plane riffle morphology.
- Key process(es): Deposition

ST:REAM

In the **ST:REAM** model, the reach is classified as depositional.

CAESAR-Lisflood



In the **CAESAR-Lisflood** model, the reach is classified as erosional (minor), with lateral deposition.

Half-yield

In the **Half-yield** method, there are three RHS data points within the vicinity of the spot check location.

One RHS point is classified as depositional in terms of the Performance Factor (P = 0.63) and Effectiveness Index (E = -1). This indicates:

- The channel is wide (possibly incised)
- In-channel flows dominant
- Frequent flows most effective at depositing
- Bar-berm building (possibly bed raising)

Two RHS points are calculated to have an immobile and stable channel bed. This indicates that the channel will act as a transfer reach for smaller sediment sizes and potentially depositional for fines. Channel banks might also be subject to erosion in high energy reaches.

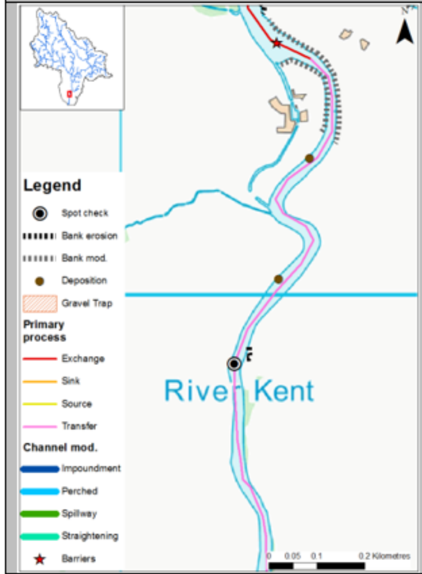
Conclusion:

- **Within this reach all methods correspond to the fluvial audit data well.**
- **CAESAR-Lisflood depicts lateral deposition which suggests that sediment will move through the system during a flood event, broadly matching the audit data. In some areas the extent of lateral deposition may be inaccurate due to the coarse ground model used.**

Figure 4-3 Results validation: Kent 03

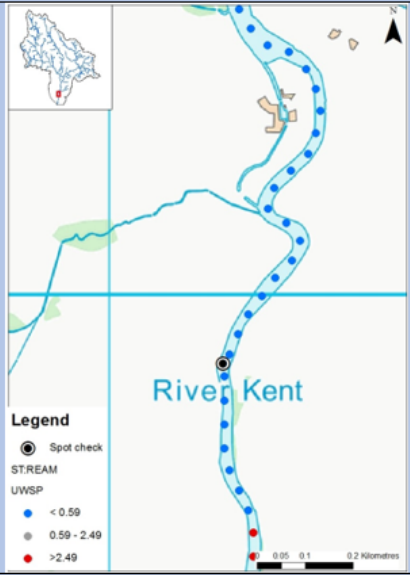
Reach: Kent_04, Watercourse: River Kent, OS NGR: 351236, 489857

Audit data



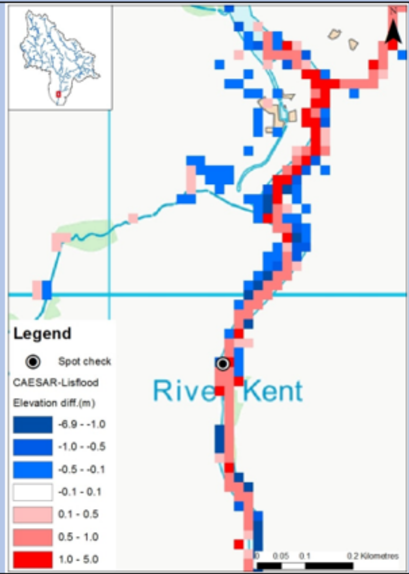
- Downstream of Kendal the channel is confined and several bedrock dominated reaches exist.
- Sediment storage in bars is limited and most is transported through the system.
- Small pockets of bank erosion and poaching.
- Key process(es): Transfer

ST:REAM



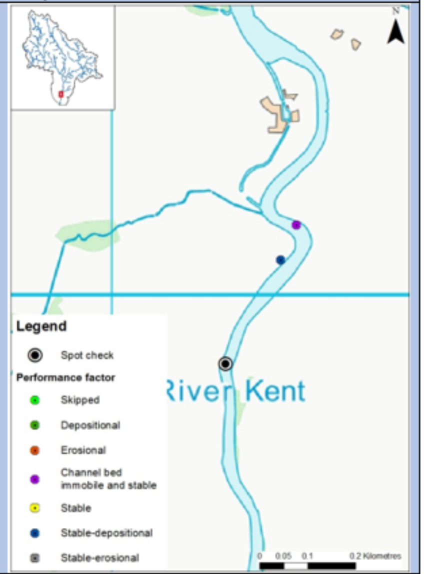
In the **ST:REAM** model, the reach is classified as depositional.

CAESAR-Lisflood



In the **CAESAR-Lisflood** model, the reach is classified as erosional, with lateral deposition upstream.

Half-yield



In the **Half-yield** method, there are two RHS data points within the vicinity of the spot check location.

One RHS point is classified as stable-depositional in terms of the Performance Factor (P = -0.12) and Effectiveness Index (E = -0.98). This indicates:

- In-channel flows dominant
- Incised/recovering
- Frequent flows most effective at depositing
- Gradual bed raising

The other RHS point Is calculated to have an immobile and stable channel bed. This indicates that the channel will act as a transfer reach for smaller sediment sizes and potentially depositional for fines. Channel banks might also be subject to erosion in high energy reaches.

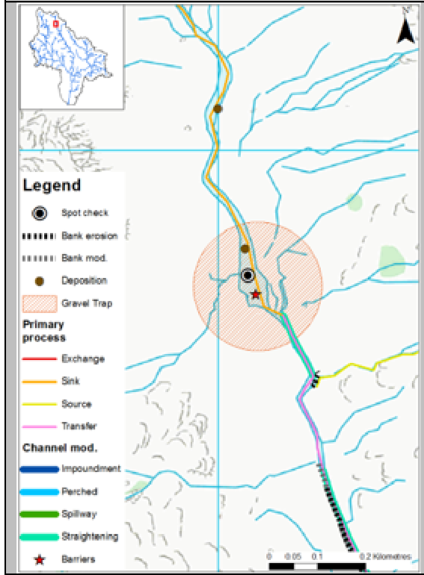
Conclusion:

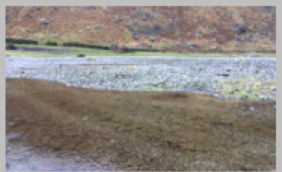
- **Within this sample reach the three tested methods present mixed results.**
- **ST:REAM classifies the reach as depositional, however this does not correspond to the Fluvial Audit.**
- **CAESAR-Lisflood classifies the reach as erosional, with lateral deposition, however due to the confined bed rock nature of the channel at this location, limited erosion occurs.**
- **The Half-Yield method best depicts the processes occurring (i.e. stable-depositional and/or channel bed immobile and stable) considering the reach is a classified as a transfer reach.**

Figure 4-4 Results validation: Kent 04

Reach: Kent_05, Watercourse: River Sprint, OS NGR: 348060,506740

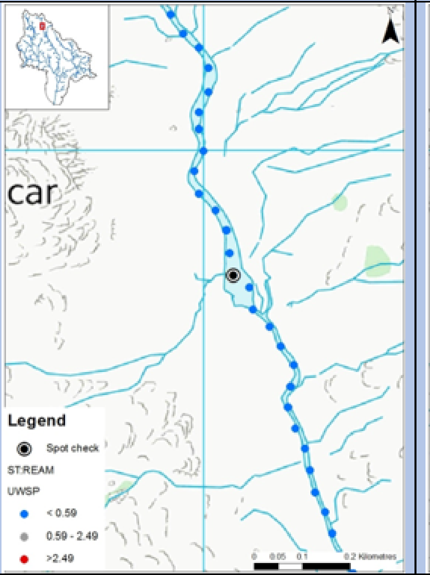
Audit data





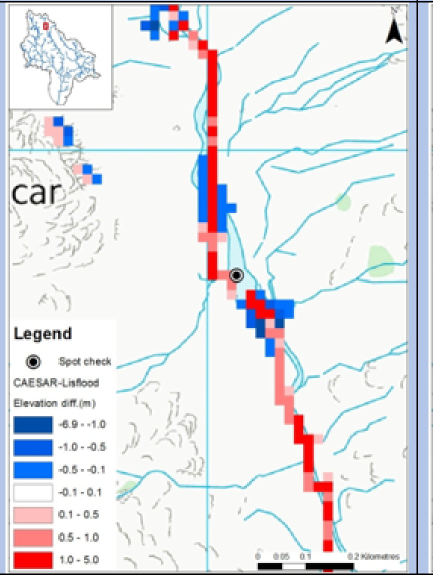
- Former quarries upstream of spot check have left a legacy of redundant mine tailings, which act as a significant sediment source.
- Gravel trap exists as the channel gradient reduces away from initial headwaters.
- The trap is no longer maintained and is full of sediment.
- Key process(es): Deposition/transportational

ST:REAM



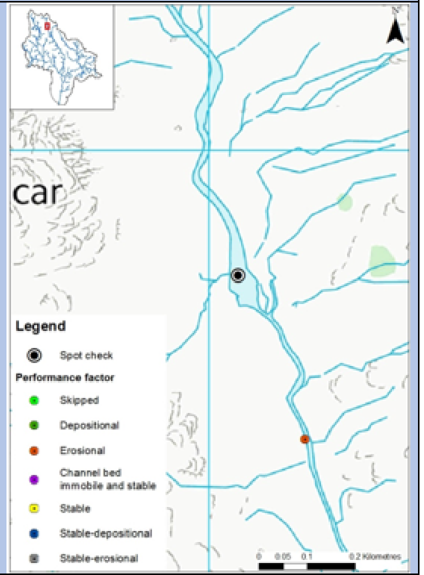
In the **ST:REAM** model, the reach is classified as depositional.

CAESAR-Lisflood



In the **CAESAR-Lisflood** model, the reach is classified as erosional, with lateral deposition in the area of the sediment trap.

Half-yield



In the **Half-yield** method there is one RHS data point located downstream of the spot check location.

The RHS point is classified as erosional in terms of the Performance Factor (P = -2.2) and Effectiveness Index (E = -1). This indicates:

- Channel is narrow/incised (significant)
- In-channel flows dominant
- Frequent flows most effective at eroding
- Bank erosion

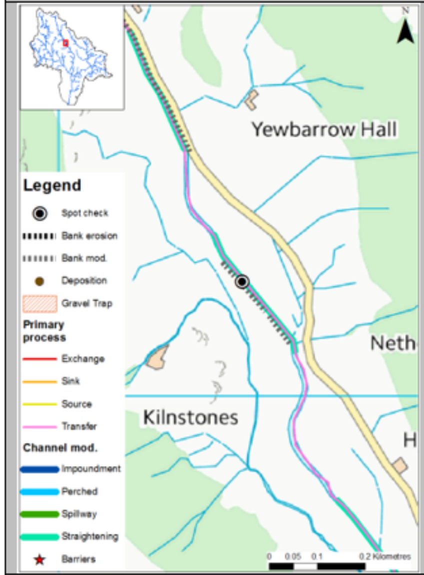
Conclusion:

- **All three methods present a different classification.**
- **Within this reach ST:REAM presents the best classification for the spot check location, based on a comparison to the fluvial audit results. However, none of the tested method depict the transportation characteristics downstream of the sediment trap.**
- **The Half Yield classifies the reach as erosional, however limited erosion was observed in the audit at the spot check location, although this matches releatively well with the conditions further downstream at the actual spot check location where erosion occurred during Storm Desmond.**
- **CAESAR-Lisflood suggests the reach is erosional, however limited erosion was observed in the audit at the spot check location.**

Figure 4-5 Results validation: Kent 05

Reach: Kent_06, Watercourse: River Sprint, OS NGR: 350381, 502239

Audit data

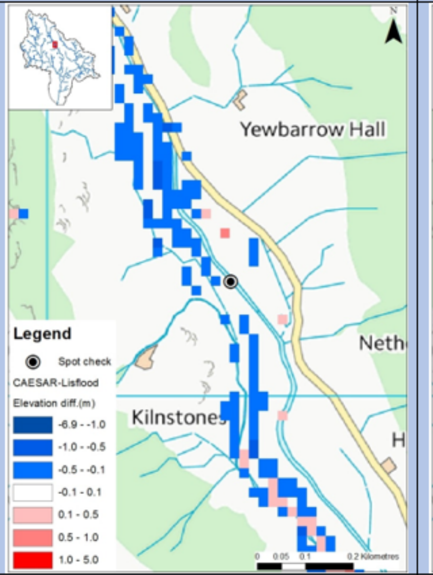


- Channel has undergone historic channel management, via training walls, embankments, straightening and dredging.
- Modifications have led to elevated velocities and minimal areas of deposition, as well as minor incision and floodplain disconnectivity.
- Key process(es): Transfer

ST:REAM

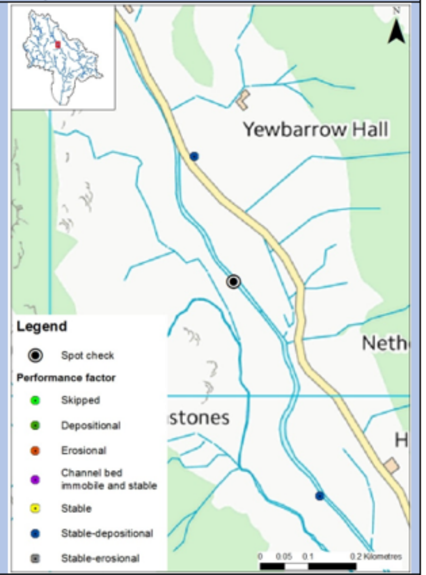
In the **ST:REAM** model, the reach is classified as depositional.

CAESAR-Lisflood



In the **CAESAR-Lisflood** model, the reach is classified as depositional, with small pockets of erosion.

Half-yield



In the **Half-yield** method, there are two RHS data points within the vicinity of the spot check location.

Both RHS points are classified as stable-depositional in terms of the Performance Factor (P = -0.32 and -0.19) and Effectiveness Index (E = -0.85 and -0.96). This indicates:

- Channel is wide (possibly incised)
- In-channel flows dominant
- Frequent flows most effective at depositing
- Bar-berm building (possibly bed raising)

Conclusion:

- **Within this reach the most suitable method for broadly characterising the dominant reach scale process is the Half-yield method.**
- **The Half-yield method predicts that the reach is relatively stable, which most closely aligns with the audit in which the reach was found to be dominated by transfer processes, with limited deposition and erosion.**
- **ST:REAM and CAESAR-Lisflood suggest depositional characteristics, which does not agree with the audit data.**

Figure 4-6 Results validation: Kent 06

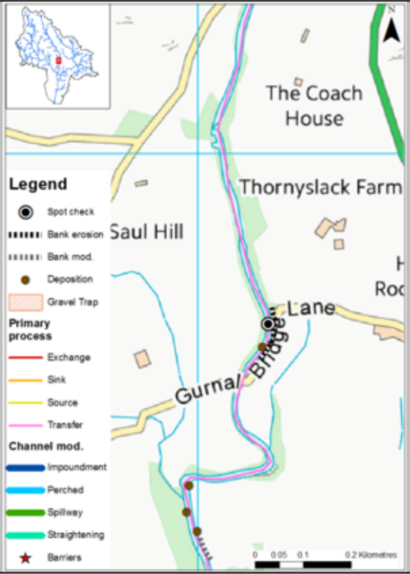
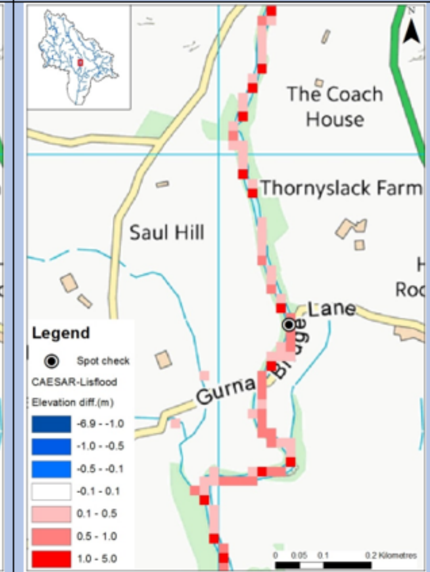
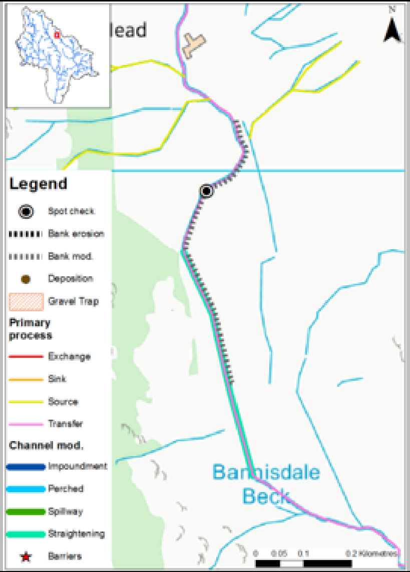
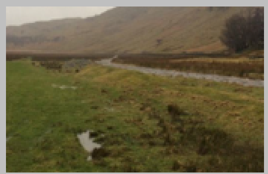
Reach: Kent_07, Watercourse: River Sprint, OS NGR: 352146, 497645			
Audit data	**ST:REAM**	**CAESAR-Lisflood**	**Half-yield**
			
• The spot check is located in a high-energy, sinuous section with some bedrock reaches • Substantial land slips on the outside meanders threatening road • Key process(es): Transfer 	In the **ST:REAM** model, the reach is classified as depositional.	In the **CAESAR-Lisflood** model, the reach is classified as erosional.	No RHS sample point available for this reach.
Conclusion: • **The Half-yield method could not be used due to the lack RHS data in the area.** • **The two methods with results available (ST:REAM and CAESAR-Lisflood) present different findings.** • **The outcome of the Fluvial Audit suggests this reach is transfer with pockets of erosion. Based on this, CAESAR-Lisflood provides the best representation of the key process within this reach.**			

Figure 4-7 Results validation: Kent 07

Reach: Kent_08, Watercourse: Bannisdale Beck, OS NGR: 351534 503960

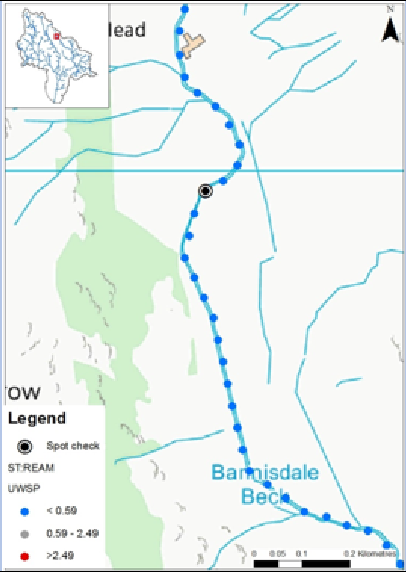
Audit data





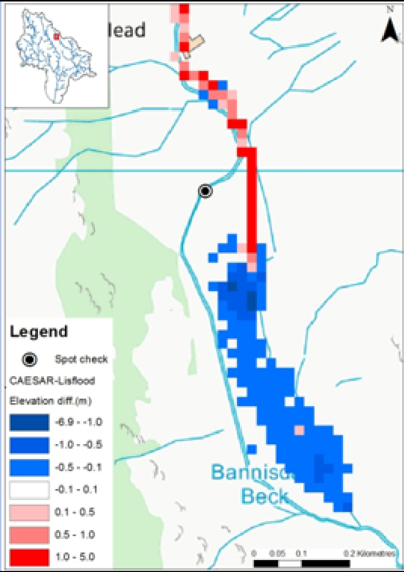
- The spot check is located downstream of steep headwaters, which deliver sediment via cobble cascades and step pools.
- Sediment delivery is exacerbated by upper catchment drainage, which will make the catchment flashy and responsive to rainfall.
- The channel has been straightened and realigned, and is now perched above the floodplain.
- Key process(es): Transfer

ST:REAM



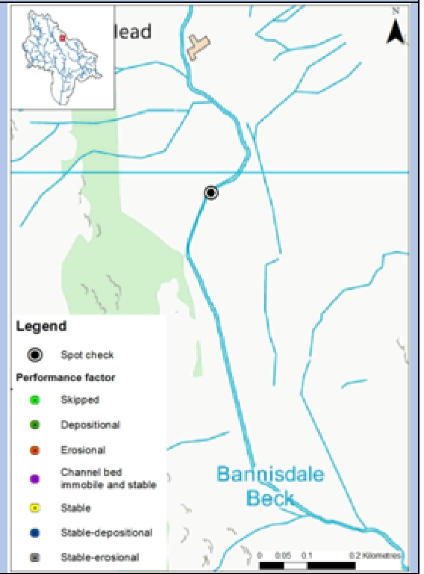
In the **ST:REAM** model, the reach is classified as depositional.

CAESAR-Lisflood



In the **CAESAR-Lisflood** model, the reach is classified as partly erosional and partly depositional.
The modelled results are offset from the existing channel location – which could indicate historic modification.

Half-yield

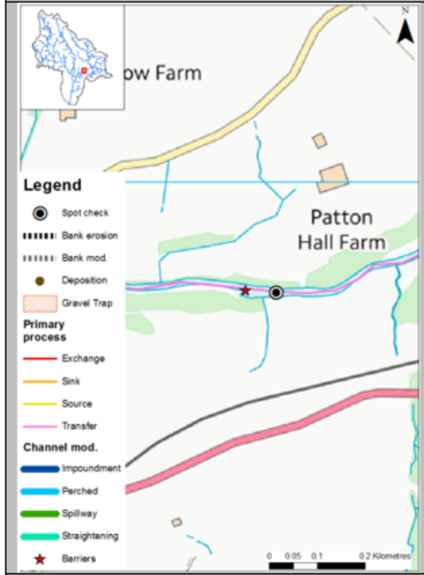
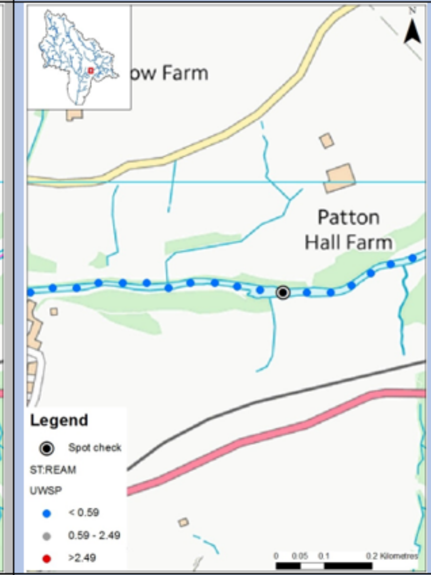


No RHS sample point available for this reach.

Conclusion:

- **The Fluvial audit characterises this reach as transfer– no extensive depositional features were noted, however the channel has historically been moved / realigned. This means that sedimentation has occurred on the bed making the channel slightly perched above the floodplain.**
- **Within this reach the most suitable method for broadly characterising the dominant reach scale process is ST:REAM (due to the perched nature of the channel).**
- **CAESAR-LISFLOOD shows the channel to be in the incorrect location due to its perched nature and the coarse LIDAR used. As a result this presents incorrect erosional and depositional processes.**
- **The Half-yield method could not be used due to the lack RHS data in the area.**

Figure 4-8 Results validation: Kent 08

<table>
<tr><td colspan="4">Reach: Kent_09, Watercourse: River Mint, OS NGR: 354652, 495770</td></tr>
<tr><td>Audit data</td><td>ST:REAM</td><td>CAESAR-Lisflood</td><td>Half-yield</td></tr>
<tr>
<td>
</td>
<td>
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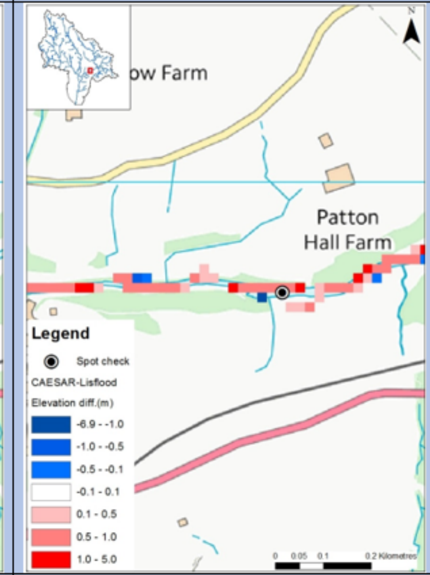
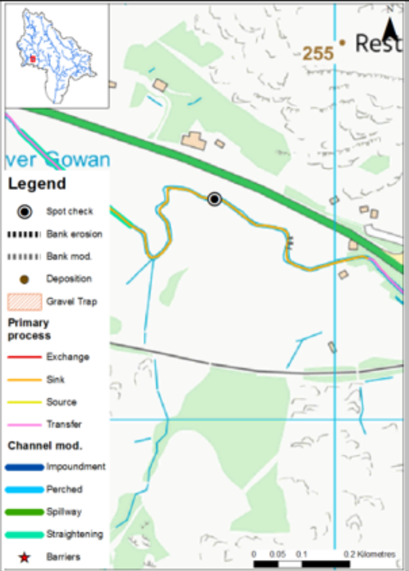
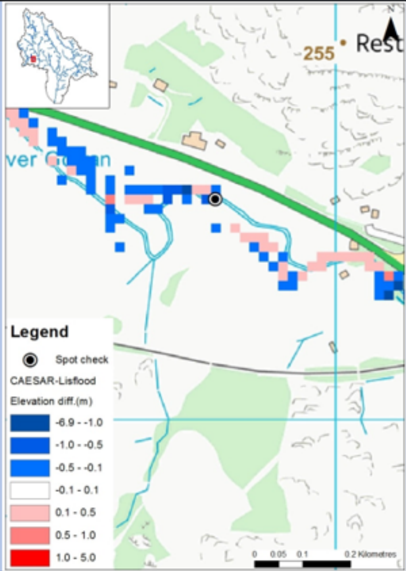
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>Channel switches from unconfined to confined floodplain areas.
Sediment deposition limited, with the exception of a few point bars where the channel gradient reduces.
Predominantly plane bed.

Key process(es): Transfer</td>
<td>In the ST:REAM model, the reach is classified as depositional.</td>
<td>In the CAESAR-Lisflood model, the reach is classified as erosional.</td>
<td>In the Half-yield method there is one RHS data point within the vicinity of the spot check location.

The RHS point is classified as stable-depositional in terms of the Performance Factor (P = -0.07) and Effectiveness Index (E = -0.99). This indicates:
In-channel flows dominant
Incised/recovering
Frequent flows most effective at depositing
Gradual bed raising</td>
</tr>
<tr><td colspan="4">Conclusion:
Within this sample reach the three tested methods present mixed results.
ST:REAM classifies the reach as depositional, however this does not correspond to the Fluvial Audit.
CAESAR-Lisflood classifies the reach as predominantly erosional, however due to the confined bed rock nature of the channel at this location limited erosion occurs.
The Half-yield method best depicts the processes occurring, i.e. a relatively stable, transfer reach with some deposition.</td></tr>
</table>

Figure 4-9 Results validation: Kent 09

Reach: Kent_10, Watercourse: River Gowan, OS NGR: 345749, 498460			
Audit data	**ST:REAM**	**CAESAR-Lisflood**	**Half-yield**
			
• Low gradient, passive meandering section. • Key process(es): Deposition 	In the **ST:REAM** model, the reach is classified as depositional.	In the **CAESAR-Lisflood** model, the reach is classified as depositional, with small pockets of erosion.	No RHS sample point available for this reach.

Conclusion:

- **Within this sample reach both ST:REAM and CAESAR-Lisflood successfully depict the processes occurring (deposition).**
- **The Half-yield method could not be used due to the lack RHS data in the area.**
- **CAESAR-Lisflood suggests erosion could occur, which may be misleading. However, the erosion is within the lowest band (from 0.1-0.5m), which suggests that it is limited in magnitude.**

Figure 4-10 Results validation: Kent 10

4.3.2 River Kent summary

Table 4.3 shows that of the 3 methods, ST:REAM most accurately represents the identified geomorphological processes in the Kent catchment, with a 60% agreement rate between the fluvial audit data and the model results, while CAESAR-Lisflood and the half-yield method have a 50% and 40% agreement rate respectively. The agreement rate calculation for the half-yield method has included spot check locations for which there are no RHS data points available as a 'negative match'. If spot check locations lacking a nearby RHS data point are excluded from the calculation, the agreement rate for the half yield method increases to 80%. This highlights that although the method performs well in terms of identifying geomorphological processes at a reach scale, being able to use it very much depends on the availability of RHS data. This will ultimately limit it being able to provide national scale coverage.

Table 4.3 Kent catchment validation summary

	Does method result agree with audit data – Y/N		
Spot check	**ST:REAM**	**CAESAR-Lisflood**	**Half-yield**
Kent_01	Y	Y	No sample point available
Kent_02	Y	N	No sample point available
Kent_03	Y	Y	Y
Kent_04	N	Y	Y
Kent_05	Y	N	N
Kent_06	N	N	Y
Kent_07	N	Y	No sample point available
Kent_08	Y	N	No sample point available
Kent_09	N	N	Y
Kent_10	Y	Y	No sample point available
Success rate matching audit	**60%**	**50%**	**40%**

4.3.3 River Stour (Dorset) and River Wharfe (North Yorkshire)

For the Stour and Wharfe catchments, the half-yield method most accurately represents the identified geomorphological processes, with a 38% and 50% agreement rate respectively between the fluvial audit data and the model results. In comparison, ST:REAM performs less well in the Stour and Wharfe catchments, with only a 13% and 38% respective agreement rate between the fluvial audit data and model results. The results are shown in Appendix D.

4.3.4 Results summary

Based on the results of the trial phase and validation, none of the results are accurate enough to provide a basis for assessment. The level of inaccurate results (>50% in many cases) could potentially produce misleading conclusions about how reaches behave and could not be used as the basis for management. Some, however, (ST:REAM and shear stress data mining) could potentially produce nationwide data, using efficient processes.

It is recommended that further trials are carried out and methods improved before a method is selected to provide a national scale model.

5 Creating pilot data sets using the shear stress data mining method

5.1 Developing a national pilot

The catchment validation study for the shear stress data mining method was extended into a parallel study to better understand the potential of using this method for creating a national data set showing the likelihood of river channel change. The aim of this test was to demonstrate possible data sets that could be produced efficiently on a national scale, not to create a working data set to use in operational practice. This work is described more fully in the project report 4 (FRS17/183/R4).

A scenario-library of maps was developed representing the potential for erosion and deposition with different characteristics, including sediment sizes and channel roughness.

Ten grain size-roughness combinations were used for each of the 3 probability maps available for the RoFSW maps (3.33%, 1% and 0.1% annual exceedance probabilities), resulting in 30 national scenarios. The resulting maps showing potential for erosion for different probabilities can be interpreted in the same way as the RoFSW map to define areas of ‘very low, low, moderate and high’ risk of erosion.

Computations to consider the difference between scenarios were used to highlight potential sensitivity of erosion to climate change. The increase in total rainfall between the 3.33% AEP precipitation and the 1% AEP represents an uplift of approximately 40% and is similar in to the projected changes in the climate impact tool for 2080 (Environment Agency, 2019). A comparison between these 2 scenarios was used to simulate the expected increases in rainfall intensity until 2080 to demonstrate how the areas susceptible to erosion may change.

This provides, for the first time, a pilot using a 2 m resolution national hydraulic data set to understand the distribution of shear stresses, and the potential for erosion in river channels across England and Wales.

The pilot scenario library could be used to help make decisions about channel maintenance planning where the appropriate mapped scenario can be selected based on the user need and local conditions.

Before any maps or modelled information on river channel change are used as part of flood risk and environment management, the maps would need to be validated in other catchments. Further work is also recommended to understand how they would be used. Any results would need to be supported with appropriate guidance for interpreting and using them.

6 Comparing results with flood hazard data

In this section, the flood risk mapping outputs from detailed hydraulic models are compared to the trial method outputs to establish whether there is any correlation. This used the 2D model outputs from local flood risk hydraulic models for the 3 trial catchments used in Report 1 (FRS17183/R1): the River Kent in Cumbria, the River Wharfe in North Yorkshire and the River Stour in Dorset. The analysis focused on these data sets rather than the broader national scale data sets, as they represent the most detailed flood hazard available for the 3 trial catchments.

The hydraulic outputs from the model (velocity and depth grids), along with a roughness value in the channel (Manning's n = 0.04), have been used to calculate shear stress estimates across the flood extent. Critical shear stress for entrainment was calculated, using an estimate for the median grain size in the catchment. The hydraulic model outputs were then classified, so that areas of shear stress that are lower than the critical shear stress for movement were classified as either transport or deposition zones, depending on whether they exceed a 'deposition threshold'.

Depth grids were only available for the hydraulic models supplied for the Kent and Wharfe catchment (no depth grids for the Stour catchment were available to this study). The analysis has therefore been limited to the Kent and Wharfe catchments.

It had been intended to compare the trial model outputs with the observed flood impacts. However, the observed flood impact data is limited within the 3 trial catchments. This is a limitation of the selected trial catchments. It is recommended that any future work in additional catchments compares the model outputs with available on-the-ground, observed flood data. This should be used to highlight where any limitations within the modelling occur and investigate potential adjustments to the models.

6.1 Kent catchment

The 2018 Kent and Gowan hydraulic model was made available to this project. This is a 1D-2D linked ISIS-Tuflow model, with a 2D grid resolution ranging from 4 to 8 m. The model results provided for the River Kent catchment only included the 2D velocity and depth grids covering the out of bank flows – the 1D portion of the results, covering in-channel flows was not included. The analysis was therefore limited to out of bank flows, and so the comparison was limited to the CAESAR-Lisflood method, as the ST:REAM and half-yield methods focus on in-channel processes. The depth and velocity grids from the 1% AEP model results were used to calculate the sediment transport condition across the flood extent and were compared to the CAESAR-Lisflood model output. This specific basin model was simulated using 25 years of rainfall data, with a digital terrain model resolution of 20 m.

The outputs show that this model can inform both past and future channel changes.

Figures 5-1 to 5-2 show the mapped results comparing the CAESAR-Lisflood method outputs and the hydraulic model results. Where the maps show minus elevation difference values (blue zones), this indicates deposition processes are dominant. The plus values (red zones) indicate erosional processes are dominant.

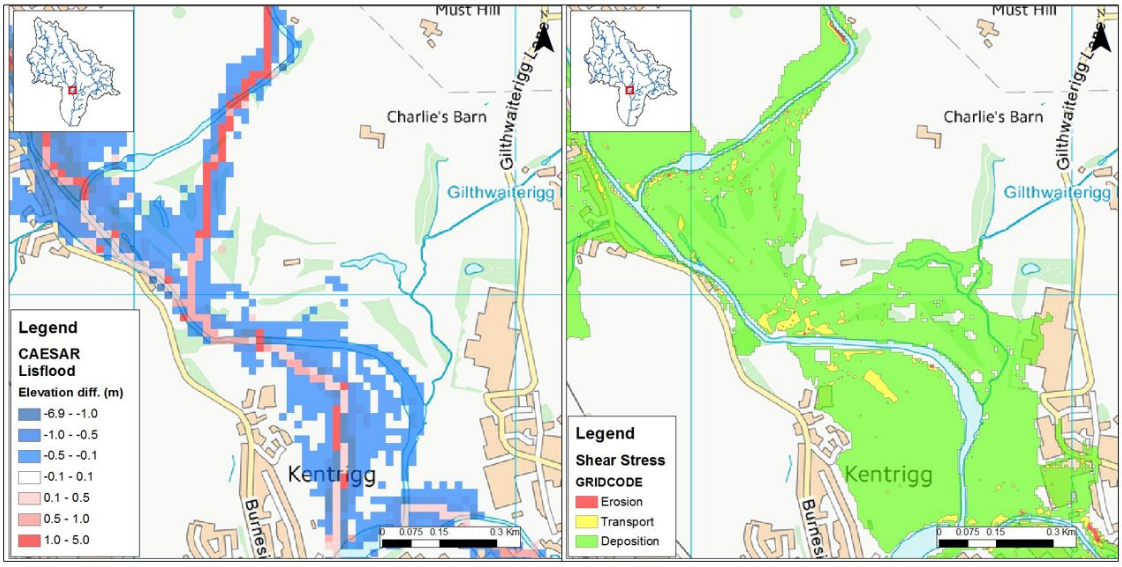


Figure 5-1 Comparison of CAESAR-Lisflood and hydraulic modelling results at Kentrigg

The representation of the River Sprint, which joins the River Kent to the north of Kentrigg, does not align well in CAESAR-Lisflood. This inaccuracy could be due to the model resolution in CAESAR-Lisflood (20 m compared to a grid resolution of 2 m in the flood risk model). The difference could be explained by CAESAR-Lisflood identifying a paleochannel (remnant of an inactive river channel) of the River Sprint. However, a review of historical maps in the area revealed that the course of the River Sprint has not been changed drastically in the last 130 years. A review of LiDAR in the areas does not reveal a clear paleochannel, although the ground is likely to have been extensively landscaped when the golf course was being constructed. A similar issue is also found on the River Kent further downstream, where CAESAR-Lisflood is not picking up the current channel route. In this location, a review of the LiDAR data clearly indicates that the CAESAR-Lisflood modelling results are following an old paleochannel route.

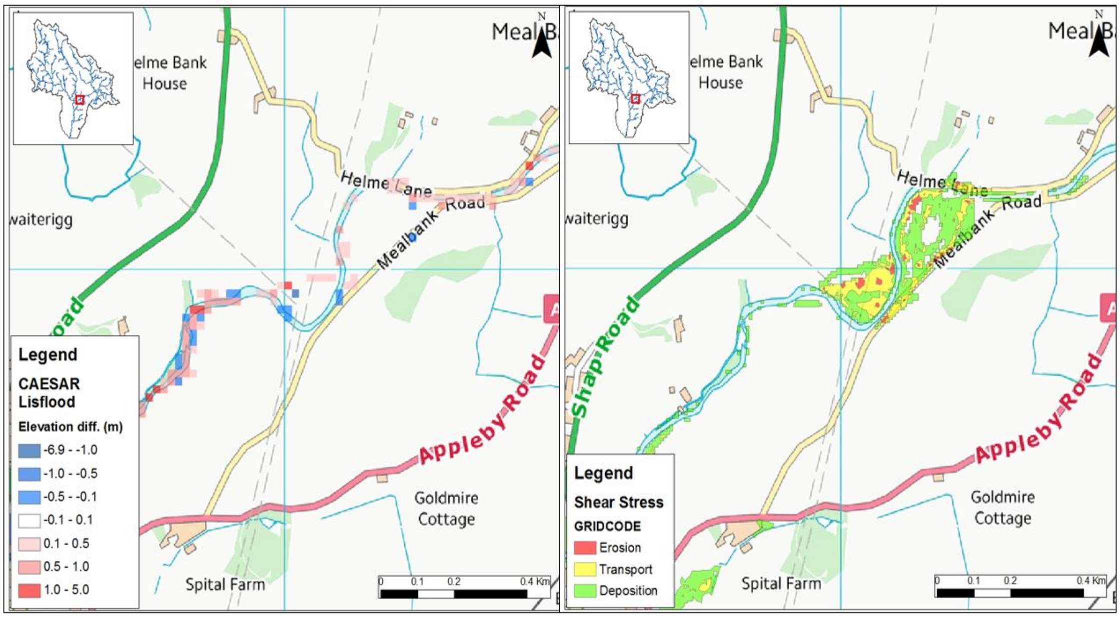


Figure 5-2 Comparison of CAESAR-Lisflood and hydraulic modelling results on the River Mint

Figure 5-2 compares the CAESAR-Lisflood method outputs and the hydraulic model results around the River Mint to the north east of Kendal. Here, there is relatively little significant geomorphic activity in the CAESAR-Lisflood results, with most of the ground elevation changes around +/- 0.1 m. A potential meander cut-off is shown in both sets of results (indicated by the black arrow), with erosion evident across the flood plain. This could potentially be flagged as a risk if there was infrastructure located here on the flood plain.

A potential meander cut-off on the River Kent is also indicated in Figure 5-3 and Figure 5-4, which display the modelling outputs downstream of Kirkbarrow within a sinuous reach of channel. Modelling results simulate erosion across the flood plain, potentially leading to a meander cut-off. While the level of detail in the model and/or DTM resolution may be limiting the accuracy of the model results in this zone, these outputs highlight a potentially significant morphological change that would need to be investigated further. Downstream of the meander bend, erosion of between 1 to 5 m in depth is modelled along the right bank. Such a significant depth of erosion is likely to indicate lateral channel migration progressing towards the right bank flood plain, or at a minimum bank instability within this reach. Consequently, both zones within this reach signify significant morphological adjustments which would require further investigation.

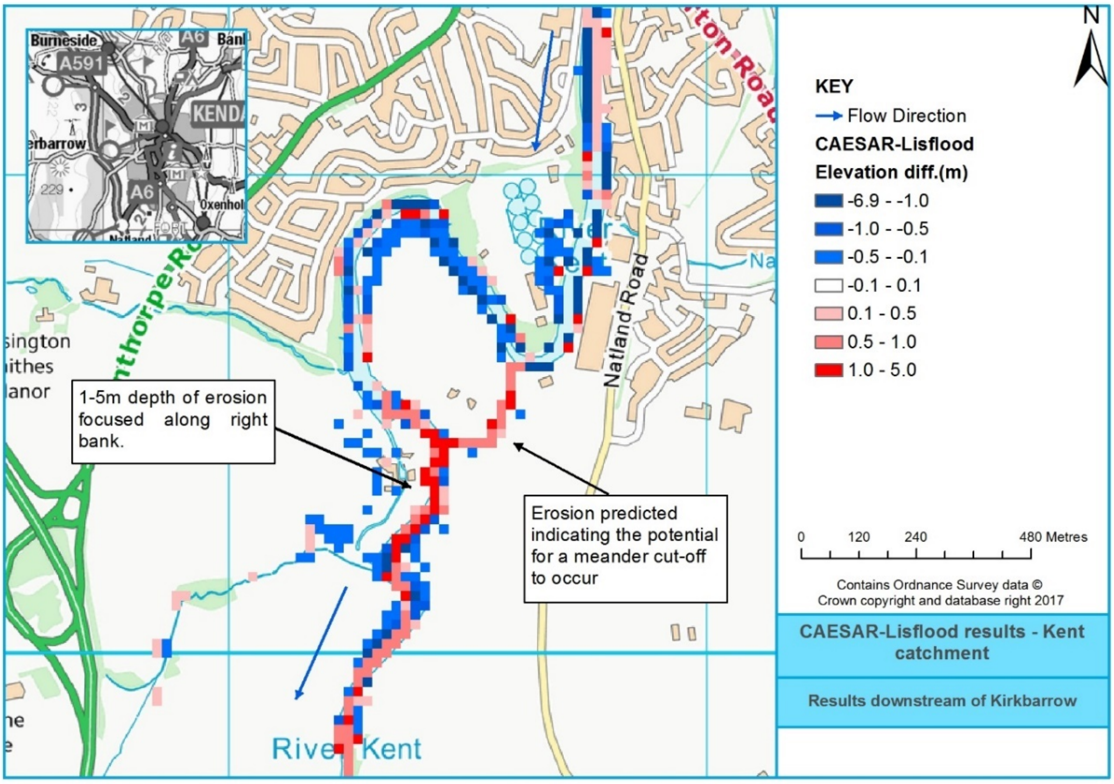


Figure 5-3 CAESAR-Lisflood modelled outputs in the River Kent catchment, indicating potential future channel evolution downstream of Kirkbarrow

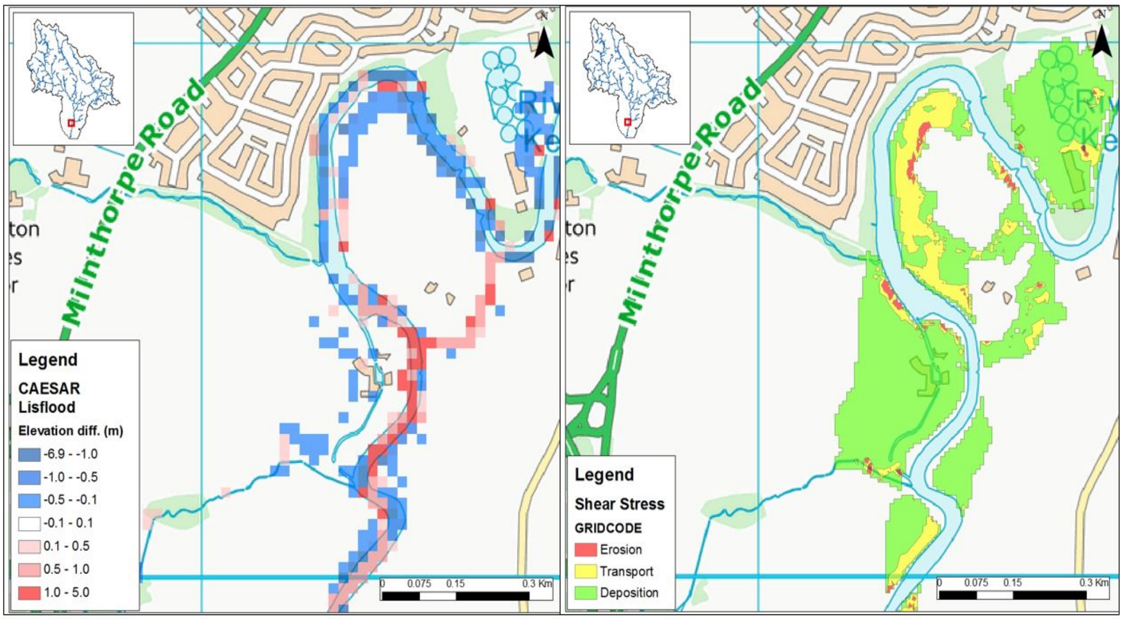


Figure 5-4 Comparison of CAESAR-Lisflood and hydraulic modelling results downstream of Kirkbarrow

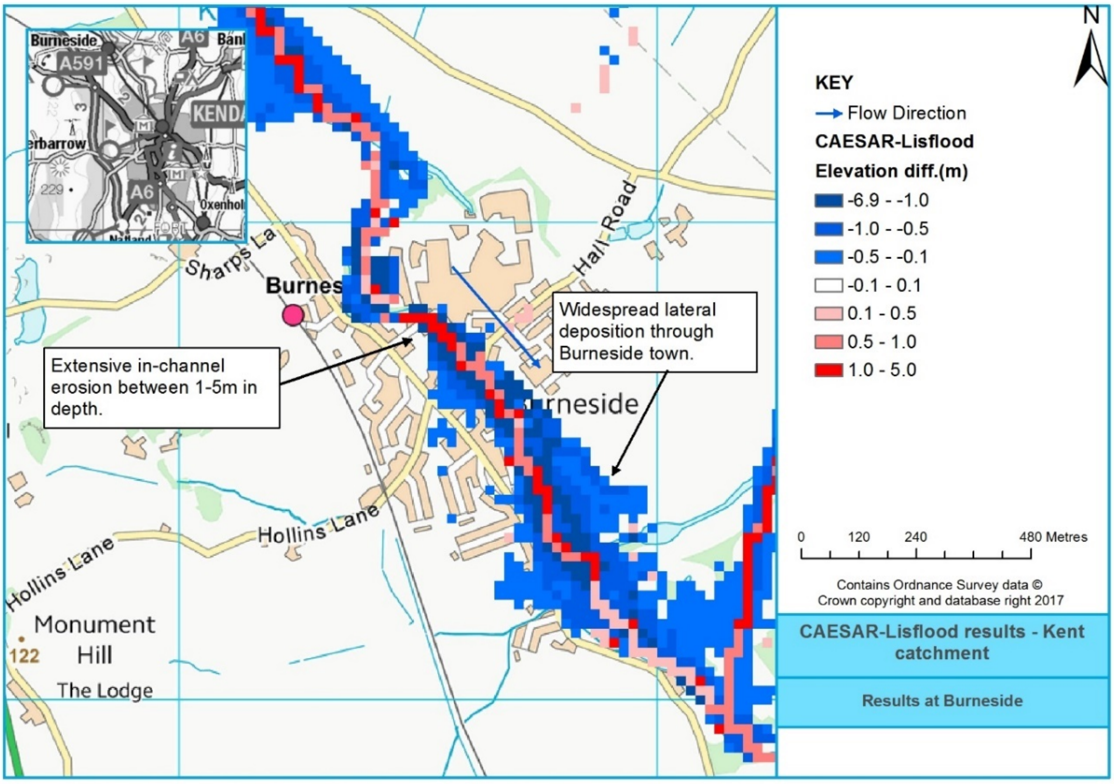


Figure 5-5 CAESAR-Lisflood modelled outputs in the Kent catchment, indicating potential future channel evolution at Burneside

Within the channel reach at Burneside, Figure 5-5 displays the modelling outputs that indicate a significant depth of in-channel erosion (1 to 5 m) at intermittent sections, combined with a widespread area of lateral deposition (indicating sediment accumulation between 1 to 6.9 m deep in some areas). This zone is of particular concern due to the built-up nature of the flood plain through Burneside town. The in-channel erosion zones are likely to indicate zones of bank instabilities associated with scour and/or undercutting, while the extent of flood plain deposition indicates that over-bank flooding is likely to occur across this zone. Both factors are significant indicators of future changes to flood hazard, requiring a more localised investigation.

6.2 Wharfe catchment

The 2014 Wharfe hydraulic model was supplied for the project. This is a 1D-2D linked ISIS-Tuflow model, with a 2D grid resolution of 10 m. The model results provided for the River Wharfe catchment included velocity and depth grids covering both the 1D (in-channel) and 2D (flood plain) model domains. A comparison with hydraulic model data was carried out for the ST:REAM and half-yield methods (CAESAR-Lisflood results are not available for the Wharfe catchment).

6.2.1 ST:REAM

The depth and velocity grids from the 50% AEP model results were used to calculate the sediment transport condition across the flood extent and were compared to the ST:REAM model output.

Figure 5-6 compares the ST:REAM method outputs and the hydraulic model results in the vicinity of Gallows Hill, between Otley and Burley in Wharfedale. In the figure key, blue, red and grey represent deposition, erosion and transport, respectively. ST:REAM indicates depositional characteristics and the model results indicates that during the 50% AEP flood, the majority of the channel is transportational or depositional.

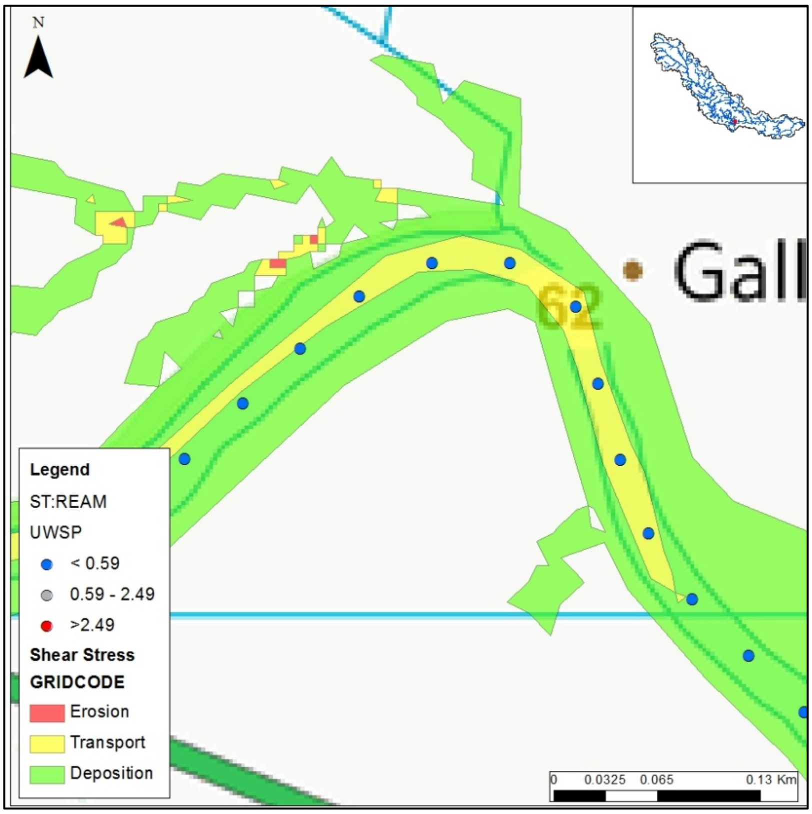


Figure 5-6 Comparison of ST:REAM and hydraulic modelling results near Gallows Hill, upstream of Otley

Figure 5-7 compares the ST:REAM method outputs and the hydraulic model results in the vicinity of the confluence of the River Washburn and River Wharfe, between Otley and Pool-in-Wharfedale. On the River Washburn, there is some positive correlation between the 2 data sets; the hydraulic model results indicate erosion close to the confluence between the River Washburn and River Wharfe, and a mixture of sediment deposition and transport further upstream. The ST:REAM data identifies this reach of the River Washburn as erosional, which corresponds with the shear stress closest to the confluence, but differs further upstream. On the River Wharfe, the ST:REAM data and the hydraulic modelling results correlate reasonably well, with depositional and depositional/transportational processes predicted in both data sets. However, from these results the ST:REAM method appears to be relatively insensitive, as depositional and transportational processes are not differentiated as they are in the hydraulic model.

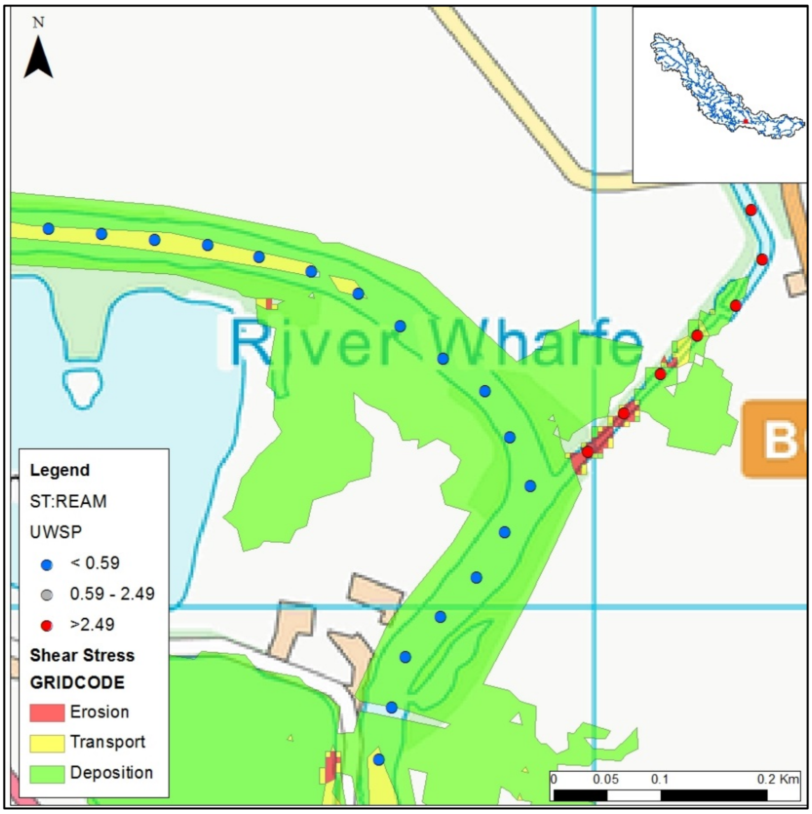


Figure 5-7 Comparison of ST:REAM and hydraulic modelling results between Otley and Pool-in-Wharfedale at the confluence of River Wharfe and River Washburn

6.2.2 Half-yield method

The sediment transport condition calculated across the extent of the 50% AEP hydraulic model results was also compared to the half-yield method outputs. The location of each half-yield point is approximate due to a low accuracy in coordinates recorded in the RHS data. As a result, there are some points that appear to be away from the river channel despite representing a river channel cross section. Consequently, the shear stress data used to compare against the half-yield classification was taken from the nearest point within the river channel.

Figure 5-8 compares the half-yield method output and the hydraulic model results in the vicinity of Burley in Wharfedale. In this location, the half-yield method classifies the river as stable-depositional, with a performance factor of 0.16 and an effectiveness index of -1. These values indicate that in-channel flows are dominant and that frequent flows are most effective at depositing, with gradual bed-raising. This correlates well with the hydraulic model results, which indicate that depositional and transportational processes are occurring within the reach during a 50% AEP flood.

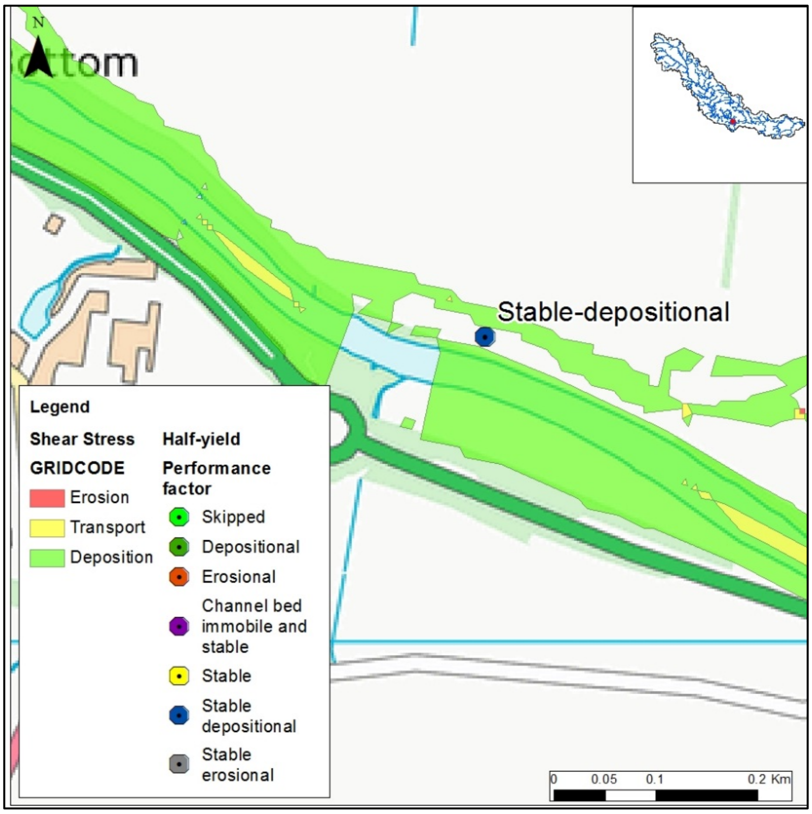


Figure 5-8 Comparison of the half-yield method and hydraulic modelling results at Burley in Wharfedale

Figure 5-9 compares the half-yield method output and the hydraulic model results just downstream of Otley. In this location, the half-yield method classifies the river as stable-depositional, with a performance factor of 0.07 and an effectiveness index of -1. These values indicate that in-channel flows are dominant and that frequent flows are most effective at depositing, with gradual bed-raising. This correlates well with the hydraulic model results, which indicate that depositional and transportational processes are occurring within the reach during a 50% AEP flood.

Figure 5-10 compares the half-yield method output and the hydraulic model results between Pool-in-Whafedale and Castley. In this location, the half-yield method classifies the river as erosional, with a performance factor of -17 and an effectiveness index of 0. These values suggest that the channel is narrow/incised, that there is a balance between in-channel and overtopping flows with potential bank erosion. There is a poor correlation with the hydraulic model results in this area, which indicate that depositional and transportational processes are occurring within the reach during a 50% AEP flood, although a small area of in-channel erosion is evident.

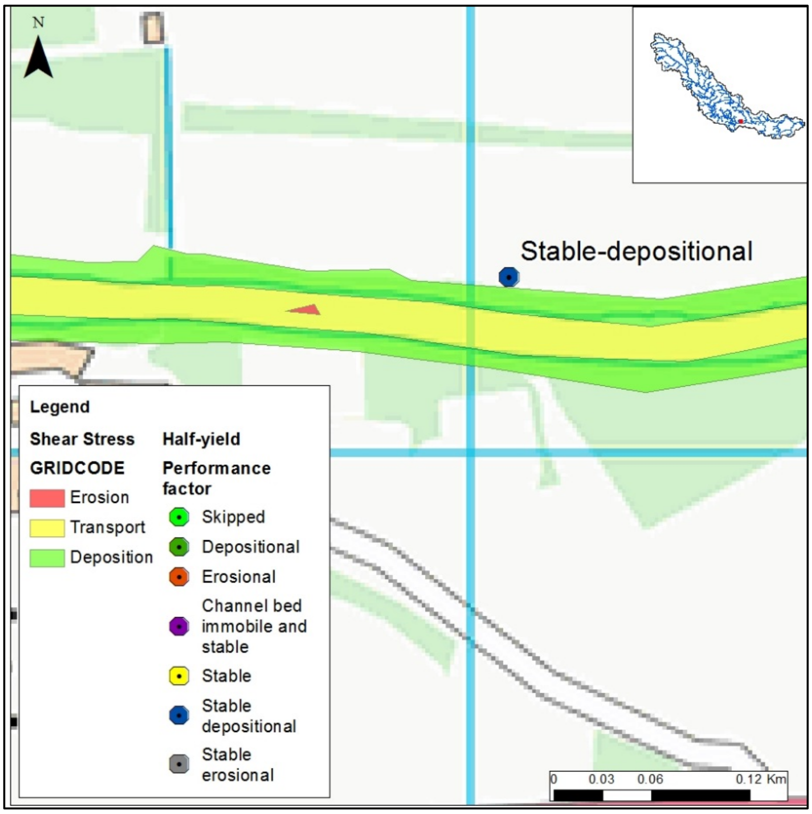


Figure 5-9 Comparison of the half-yield method and hydraulic modelling results downstream of Otley

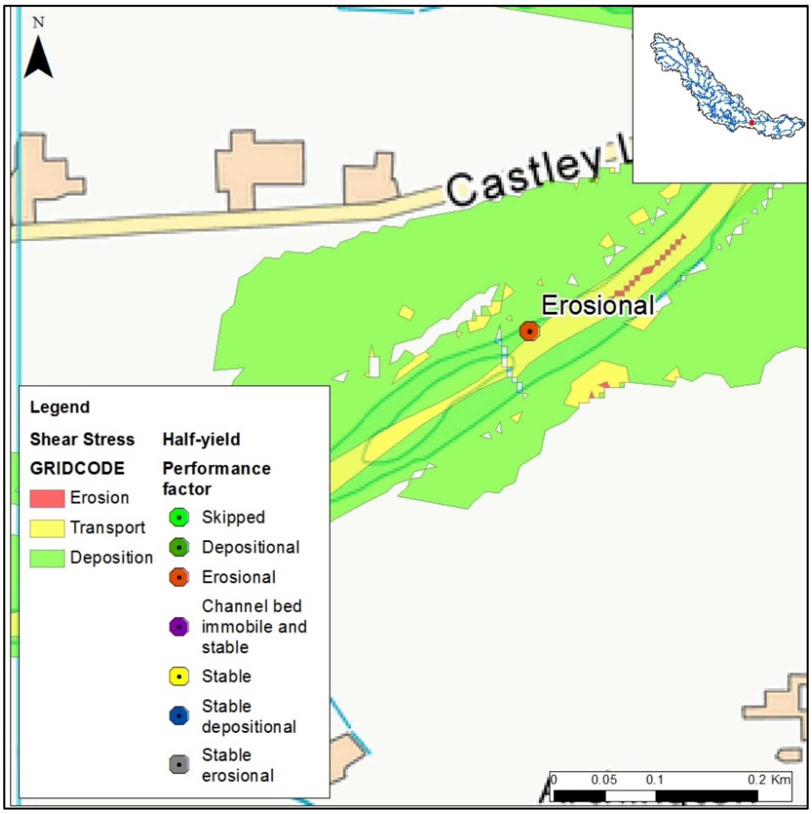


Figure 5-10 Comparison of the half-yield method and hydraulic modelling results between Pool-in-Wharfedale and Castley

6.3 Summary

Overall, the CAESAR-Lisflood results in the River Kent catchment are limited by their resolution. In comparison, the hydraulic modelling results are able to pick up finer detail, due to their higher resolution. A full comparison has not been possible due to 1D model results for the in-channel results not being available. CAESAR-Lisflood results could be used to highlight areas where meander cut-throughs could potentially threaten infrastructure on the flood plain (as shown in Figure 5-4). In some cases, this detail is also shown in the hydraulic modelling results (as shown in Figure 5-2).

In the River Wharfe catchment, the ST:REAM results correlated well with the hydraulic model results across the catchment. The majority of the ST:REAM data points indicated depositional characteristics across the catchments, and the hydraulic model results indicated either depositional or transportational characteristics. There was some variation between the half-yield method and the hydraulic model results. Half-yield points that indicated erosional characteristics within the catchment tests had negative correlations with the hydraulic model results, mostly because there are very few areas of erosion found in the hydraulic modelling outputs across the catchment. The remaining 3 half-yield points all indicated various levels of deposition, from stable depositional to possible deposition of fine sediment. These all correlated positively with the shear stress data in adjacent locations, which predominantly indicates either deposition or transport of sediment.

A wider consideration is that many rivers are not showing significant progressive change (either incision or deposition) because of feedbacks within the fluvial system or because erosion on the rising limb to the peak of the hydrograph is then subsequently compensated for by deposition on the falling limb. This means that approaches (such as ST:REAM and the shear stress data mining method) that are based on a single value on a hydrograph (for example, the peak) to represent the flow may miss this and result in a misleading impression of the processes operating in the channel. This does not undermine the value of the national tools, but it should be recognised as a limitation of the methods tested. If these approaches are taken forward into operational use this may require further research to investigate how feedbacks can be incorporated into the methods.

7 Incorporating influencing factors into the trialled methods

7.1 Overview

The literature review and analysis carried out for this project (described in FRS17183/R1) showed the patterns of geomorphological impacts of a flood event greatly depend on influencing factors which, together, determine the channel response in terms of erosion and/or deposition. This section considers how the influencing factors could be incorporated into the methods trialled in this report.

7.2 ST:REAM

ST:REAM was designed to be conceptually simple and does not explicitly account for influencing factors. The main driving factor in its development was to produce a method that could predict system-wide trends, and therefore the model was not intended to work at a local scale.

The method identifies reaches by assessing the variability of sediment transport capacity across the whole river branch and subsequently creating reaches by minimising variability within a reach, while maximising variability between reaches. Local scale variability (for example, within a 50 m river reach) would need to be extreme in order to influence overall reach scale values of sediment transporting capacity. It is therefore unlikely that a separate reach would be created for a local scale influencing factor, unless it was extreme. The ability to model local scale detail is therefore considered to be limited for the majority of the influencing factors identified and described in this research project.

The method is limited when there is an influence on sediment transfer in the system (for example, a structure such as a weir that traps sediment). The model does not route sediment, and therefore does not model sediment transfer, instead assuming an infinite supply of sediment which is not the case in reality. Consequently, reaches with a series of check dams or weirs are not well represented. In addition, ST:REAM is an in-channel method, so will not account for interactions with overbank infrastructure during large flood events.

Nonetheless, although it is important to acknowledge these limitations of the method, it is possible that local scale influencing factors could be incorporated by adding in extra detail following the initial ST:REAM model run. This would essentially result in a two-stage approach, for which 2 levels of results would be generated:

1. **Standard ST:REAM model** - general representation of main processes based on reach scale results, applied at a national scale
2. **Influencing factors decision support framework** – standard ST:REAM model results combined with data investigation to assess results at a local scale (for example, on a catchment by catchment basis) as and when needed. For example, the Environment Agency's asset management data could be reviewed to locate channel modifications, which cause narrowing/widening and/or changes in channel gradient (for example, dams, weirs, culverts or bridges) that affect the channel change. This level of additional investigation could flag any areas where influencing factors have the potential to influence the sensitivity of a watercourse to change during normal flows and flood events. In some cases, this could be taken a step further with additional calculations: stream power could be calculated at each specific point of channel modification to identify any significant variations to the average reach-scale values. Where the calculation identifies key, local scale differences to the reach-based

representation of morphological processes according to ST:REAM, this can then be incorporated into an updated data set of results.

The potential ways in which each of the influencing factors could be incorporated into the ST:REAM method is explored in further detail in Table 6.1 below. This is illustrated in Appendix C (C1).

Table 6.1 Incorporating influencing factors into the ST:REAM method

Influencing factor	How to incorporate influencing factor	Data sets required
Bedrock/valley confinement	Bedrock already included. Reviewed/considered when validating results.	Fluvial audit Aerial imagery BGS drift/solid geology maps plus confinement tool
Channel slope (natural)	This is already incorporated into the method as a key factor in the stream power calculation.	
Sediment supply and connectivity	Identify where substantial deposition has occurred which has changed channel geometry/gradient. Incorporate in rule-based approach following on from national, broad-scale model to flag locations where sediment deposition may alter the channel's sensitivity to flood flows. If the channel geometry/gradient has changed, recalculate stream power based on new geometry.	Fluvial audit Pre and post flood survey of sediment accumulation
Magnitude, duration and sequencing of flows	The magnitude of QMED flows is already incorporated into the method, although extreme events are not represented. It is not possible to incorporate the duration and sequencing of flows into the method.	
Large wood and riparian vegetation	Identify where key woody material is present. Incorporate in rule-based approach following on from national, broad-scale model to flag locations where the presence of woody material may alter the channel's sensitivity to flood flows. Local changes to stream power could be recalculated with additional information on size and alignment of large wood. If the channel geometry/gradient has changed in response to the placement of large wood, recalculate stream power based on new geometry. This factor is considered to be potentially difficult to incorporate as it assumes immobility of large wood during a flood event.	Fluvial audit Aerial imagery
Flood plain infrastructure	Identify flood plain infrastructure (such as pylons, roads, urban development, embankments). Incorporate in rule-based approach following on from national, broad-scale model to flag locations where infrastructure may alter the channel's sensitivity to flood flows. For example, local changes to stream power could be recalculated with additional information on the type of flood plain infrastructure and its potential to cause flow constriction (a decrease in channel width), if these are not already identified in the DTM. Generally, this factor is considered to be potentially difficult to model if the infrastructure does not cause a	Flood asset data Fluvial audit OS MasterMap

Influencing factor	How to incorporate influencing factor	Data sets required
	reduction in channel width as ST:REAM only considers in-channel flows.	
Channel modification	Identify areas where channel modification has taken place (channelisation, straightening, realignment). Incorporate in rule-based approach following on from national, broad-scale model to flag locations where channel width/depth alterations may alter the channel's sensitivity to flood flows. Local changes to stream power could be recalculated with additional information on the type of channel modification and its potential to cause narrowing/widening and/or changes in channel gradient, if these are not already identified in the DTM.	Channel maintenance records Current LiDAR/IHM data sets Historic mapping Aerial imagery
Channel maintenance	Identify historic and contemporary channel maintenance/dredging. Incorporate in rule-based approach following on from national, broad-scale model to flag locations where channel maintenance/dredging may alter the channel's sensitivity to flood flows. This factor is considered to be potentially difficult to incorporate as it relies on accurate recording of works (areal extent and depth of removal) and pre- and post-survey data.	Channel maintenance records
In-channel structures	Identify weirs, bridges and culverts. Incorporate in rule-based approach following on from national, broad-scale model to flag locations where in-channel structures may alter the channel's sensitivity to flood flows. Local changes to stream power could be recalculated with additional information on structure. For example, a weir locally controls river gradient but the DTM from which ST:REAM slopes are generated may not detect these changes in gradient. If the weir was identified as a local factor and the ST:REAM calculation points were automatically located immediately upstream and downstream of the weir crest, it would highlight a significant difference in energy that could create a new reach.	Flood asset data Fluvial audit OS MasterMap
Asset failure	Identify where bank modification or flood defences are in disrepair or have failed. Incorporate in rule-based approach following on from national, broad-scale model to flag locations where failure of bank modification or flood defences may alter the channel's sensitivity to flood flows. Check records to see if failure involved altered channel geometry. If the channel geometry has changed, recalculate stream power based on new geometry if there is enough asset inspection record data.	Fluvial audit Asset inspection records
Land use changes	Land use could potentially be incorporated by adjusting the QMED values for individual branches of a catchment to represent changes in flow associated with land use changes. The CEH equation is used to calculate QMED and this equation includes land use. It would	OS mapping Aerial imagery CORINE

Influencing factor	How to incorporate influencing factor	Data sets required
	therefore be possible to adjust the equation to account for land use.	

7.3 CAESAR-Lisflood

Of the 4 methods trialled, CAESAR-Lisflood most readily lends itself to incorporating influencing factors within the model setup. At a broad scale, factors can be grouped into the following 3 categories:

1. Structures that are, in theory, fixed and immoveable, for example, weirs.
2. Actions that lead to channel modification, for example, dredging.
3. Features that are already incorporated in CAESAR-Lisflood, for example, channel slope.

The potential ways in which each of the influencing factors could be incorporated into the CAESAR-Lisflood method are explored in further detail in Table 6.2 below.

CAESAR-Lisflood was run in catchment mode for the trial phase of this project, using rainfall data. It is also possible to run the model in reach mode, which requires point discharge data. Running in reach mode, potentially using flow data from an existing hydraulic model, would make it possible to explore influencing factors on a very small scale (2m). This could include, for example, a series of in-channel wood jams, channel dredging, and asset failure, such as the collapse of bank protection or weir failure.

Table 6.2 Incorporating influencing factors into CAESAR-Lisflood

Influencing factor	How to incorporate influencing factor	Data sets required
Bedrock/valley confinement	Valley confinement will already be accounted for in the LiDAR data. The presence of bedrock can be incorporated by editing the bedrock layer to represent areas of bedrock.	Fluvial audit BGS drift/solid geology maps plus confinement tool
Channel slope (natural)	Channel slope (natural) will already be accounted for in the LiDAR data.	
Sediment supply and connectivity	Already incorporated within the CAESAR-Lisflood model, due to the ability to account for lateral erosion.	
Magnitude, duration and sequencing of flows	The magnitude and duration of a flood event would already be accounted for in the rainfall data. The sequencing of floods could also potentially be incorporated by running multiple rainfall events within the model simulation.	Rainfall data
Large wood and riparian vegetation	The resolution of the modelling carried out for this study (20 m grid size) limits the potential to incorporate such structures. However, could be represented in higher resolution models (<5 m grid size) as weirs or local increased roughness values when in the form of logjams.	Fluvial audit
Flood plain infrastructure	‘Hard’ flood plain infrastructure, such as pylons could be added to the bedrock DEM layer, creating cells that cannot be eroded. These would have to be identified and added manually to the DEM. Sub-pixel size structures can be dealt with in the code by modifying the width of the channel through which water can flow. This could be difficult to automate. Infrastructure represented in a readily available, national GIS layer, such as flood	Flood asset data

Influencing factor	How to incorporate influencing factor	Data sets required
	defences, could potentially be burnt into LiDAR data using a semi-automated method in ARCGIS.	
Channel modification	Works that alter the channel width/depth, such as channelisation and past realignment, will already be present in the LiDAR data and therefore DEM used in the model (depending on the date of the LiDAR flight).	
Channel maintenance	Dredging (removing in-channel material) can be readily simulated by modifying the elevation of the channel within the DEM. Accurate recording of works (areal extent and depth of removal) and pre- and post-survey data would be necessary. According to Prof. Coulthard, removing in-channel material has already been successfully simulated in CAESAR-Lisflood models (conversations had through this project).	Channel maintenance records
In-channel structures	In-channel structures, such as weirs, could be added to the bedrock DEM layer, creating cells that cannot be eroded. These would have to be identified and added manually to the DEM. Sub-pixel size structures can be dealt with in the code by modifying the width of the channel through which water can flow.	Flood asset data Fluvial audit data OS Mastermap
Asset failure	Post flood impacts picked up in an audit and included in updated model geometry. Where any significant change/failure is identified, such as damage, the model could be updated and represented in DEM. May be limited due to coarse resolution.	Fluvial audit Asset inspection records
Land use changes	The impacts of land use change include changes to surface run-off rates, as well as changes to channel/flood plain erodibility. These will be difficult to represent in terms of parameters. It is possible to change the parameters for vegetation cover in CAESAR, in terms of the erodibility of banks and hydrology/run-off changes. However, this would need further consideration. Areas of reforestation for example, could be factored in by altering the ‘m’ factor.	OS mapping Aerial imagery CORINE

7.4 The half-yield method

The half-yield method is less well suited than ST:REAM for incorporating influencing factors. This is due to its cross section approach, which does not account for overall reach conditions. However, if modification has created a long-term influence on slope or channel geometry, these modifications could be picked up within the model.

The method is similar to ST:REAM in that it is limited when there is an influence on sediment transfer in the system (for example, a structure such as a weir that traps sediment). The model does not route sediment, and therefore does not model sediment transfer, instead assuming an infinite supply of sediment, which is not the case in reality. Consequently, reaches with a series of check dams or weirs are not well represented.

It will be essential to use a decision support framework to consider the effect of influencing factors and conditions (not only channel modifications, but also conditions such as land use and geology).

The support system would help to identify the nature of change at a specific location. A two-stage approach could be adopted as follows:

1. initial national-scale model using RHS data set
2. influencing factors decision support framework – supplement initial national-scale model with targeted local data investigation, where additional local-scale data is available

The potential ways in which each of the influencing factors could be incorporated into the half-yield method are explored in further detail in Table 6.3.

Table 6.3 Incorporating influencing factors into the half-yield method

Influencing factor	How to incorporate influencing factor	Data sets required
Bedrock/valley confinement	Bedrock is already incorporated into the method (from the RHS data).	
Channel slope (natural)	Channel slope (natural) is already incorporated into the method (from the RHS data).	
Sediment supply and connectivity	Identify where substantial deposition has occurred which has changed channel geometry/gradient. Incorporate in rule-based approach following on from initial, national-scale model to flag locations where sediment deposition may alter the channel's response to flood flows. If the channel geometry/gradient has changed, recalculate stream power based on new geometry. Ability to incorporate in method relies on either the deposition occurring in close proximity to an RHS cross section, or, if channel survey data is available, a new cross section could be generated to calculate the method at the new location.	Fluvial audit Pre and post flood survey of sediment accumulation
Magnitude, duration and sequencing of flows	Flow magnitude is partially incorporated into the method as it uses the flow duration curve (including annual peak flows), although individual flood events are not modelled. The sequencing of flows cannot be considered in the model.	
Large wood and riparian vegetation	Identify where key woody material is present. Incorporate in rule-based approach following on from initial, national-scale model to flag locations where the presence of woody material may alter the channel's response to flood flows.	Fluvial audit Aerial imagery
Flood plain infrastructure	Identify flood plain infrastructure (such as pylons, roads, urban development, embankments). Incorporate in rule-based approach following on from initial national-scale model to flag locations where infrastructure may alter the channel's response to flood flows. This factor, however, is considered to be difficult to incorporate as the method does not account for interactions with overbank infrastructure.	Flood asset data Fluvial audit OS MasterMap
Channel modification	Identify areas where channel width/depth alterations have taken place (such as channelisation, straightening, realignment). Incorporate in rule-based approach following on from initial, national-scale model to flag	Channel maintenance records Current LiDAR / IHM datasets

Influencing factor	How to incorporate influencing factor	Data sets required
	locations where channel modification may alter the channel's response to flood flows. There is a significant limitation in that the location of the channel width/depth alterations may not be located within the vicinity of the RHS data points. However, if local channel survey data is available, a new cross section could be generated to calculate the method in the vicinity of the channel width/depth changes.	Historic mapping Aerial imagery
Channel maintenance	Identify historic and contemporary channel maintenance/dredging. Incorporate in rule-based approach following on from initial national-scale model to flag locations where channel maintenance/dredging may alter the channel's response to flood flows. This factor is considered to be potentially difficult to incorporate as it relies on accurate recording of works (areal extent and depth of removal) and pre- and post-survey data. In addition, it would also be reliant on the works having been completed in close proximity to the available cross section. Alternatively, if survey data is available, a new cross section could be generated to calculate the method at the new location.	Channel maintenance records
In-channel structures	Identify weirs, bridges and culverts. Incorporate in rule-based approach following on from initial national-scale model to flag locations where in-channel structures may alter the channel's response to flood flows. There is a significant limitation due to the location of RHS data points – these are not likely to be near the structure (due to RHS survey technique). However, if local channel survey data is available, a new cross section could be generated to calculate the method at the structure.	Flood asset data Fluvial audit OS MasterMap
Asset failure	Identify where bank modification or flood defences have failed. Incorporate in rule-based approach following on from initial national-scale model to flag locations where failure of bank modification or flood defences may alter the channel's response to flood flows. Check records to see if failure involved altered channel geometry. If the channel geometry has changed, recalculate method based on new geometry if there is enough asset inspection record data. Ability to incorporate in method relies on either the works having been completed in close proximity to an RHS cross section, or, if channel survey data is available, a new cross section could be generated to calculate the method at the new location.	Fluvial audit Asset inspection records
Land use changes	Identify significant areas of land use change. Incorporate in rule-based approach following on from initial, national-scale model to flag locations where land use changes may influence the channel and its response to flood flows.	OS mapping Aerial imagery CORINE Flow gauge records

Influencing factor	How to incorporate influencing factor	Data sets required
	Land use changes could potentially be incorporated into the hydrology by modifying the flow duration curves (FDCs). The raw gauge data could be examined to assess how representative it is, that is to assess if the land use change is likely to have impacted the flows recorded at the gauge location. A shift in the gauged discharge since the land use change has taken place may suggest that there has been an impact on flows that can be associated with the change. This could be incorporated in the method by modifying the gauge data.	

7.5 Shear stress data mining method

For the shear stress data mining method several of the influencing factors are likely to be accounted for in the LiDAR data and therefore already incorporated into the method (for example, valley confinement, channel slope and channel modification in terms of straightening/realignment). The magnitude of flows is also already incorporated into the method (in terms of the 3.3% and 1% AEPs), although it is not possible to account for the duration and sequencing of flows. The majority of influencing factors would be difficult to account for due to the inability to update the model with specific information and rerun the underlying national scale model (the risk of flooding from surface water complex model outputs). Therefore, the only variables that can be updated in the shear stress data mining method are sediment size and Manning's roughness.

Table 6.4 Incorporating influencing factors into the shear stress data mining method

Influencing factor	How to incorporate influencing factor	Data sets required
Bedrock/valley confinement	Valley confinement will already be accounted for in the LiDAR data.	
Channel slope (natural)	Channel slope (natural) will already be accounted for in the LiDAR data.	
Sediment supply and connectivity	Identify significant depositional areas. Incorporate in rule-based approach to flag locations where significant areas of deposition may affect the channel's sensitivity to flood flows. Modify the roughness and grain size values in the shear stress data mining method to represent significant areas of deposition and rerun the model at a catchment scale.	Fluvial audit Pre- and post-flood survey of sediment accumulation
Magnitude, duration and sequencing of flows	The magnitude of flows is already incorporated into the method (3.3% and 1% AEPs). It is not possible to incorporate the duration and sequencing of flows into the method.	
Large wood and riparian vegetation	Identify where large wood is present in the channel. Incorporate in rule-based approach following on from initial national-scale model to flag locations where large wood may alter the channel's response to flood flows. It may be possible to modify the roughness value in the shear stress data mining method to represent large wood and rerun the model.	Fluvial audit Aerial imagery

Influencing factor	How to incorporate influencing factor	Data sets required
Flood plain infrastructure	Identify flood plain infrastructure. Incorporate in rule-based approach following on from initial national-scale model to flag locations where flood plain infrastructure may alter the channel's response to flood flows. Some elements of flood plain infrastructure, such as embankments, will already be present in the LiDAR data and therefore DEM used in the model (depending on the date of the LiDAR flight).	Flood asset data Fluvial audit OS MasterMap
Channel modification	Identify historic channel modification. Incorporate in rule-based approach following on from initial national-scale model to flag locations where channel modification may alter the channel's response to flood flows. Works that have altered the channel course, such as channelisation and past realignment, will already be present in the LiDAR data and therefore DEM used in the model (depending on the date of the LiDAR flight).	Channel maintenance records Current LiDAR/IHM data sets Historic mapping Aerial imagery
Channel maintenance	Identify historic and contemporary channel maintenance/dredging. Incorporate in rule-based approach following on from initial national-scale model to flag locations where channel maintenance/dredging may alter the channel's response to flood flows. This factor is considered to be potentially difficult to incorporate as it relies on accurate recording of works (areal extent and depth of removal) and pre- and post-survey data. It may be possible to modify the roughness in the shear stress data mining method to represent vegetation clearance, and rerun the model at a catchment scale.	Channel maintenance records
In-channel structures	Identify weirs, bridges and culverts. Incorporate in rule-based approach following on from national, broad-scale model to flag locations where in-channel structures may alter the channel's sensitivity to flood flows. Some structures, such as large weirs, may already be incorporated in the DEM, and would therefore already be incorporated into the model.	Flood asset data Fluvial audit OS MasterMap
Asset failure	Identify where bank modification or flood defences have failed. Incorporate in rule-based approach following on from initial national-scale model to flag locations where failure of bank modification or flood defences may alter the channel's response to flood flows. It may be possible to modify the roughness value in the shear stress data mining method to represent asset failure and rerun the model. For example, the failure of bank protection could expose fine sediment in the bank. This could be represented in the model by changing the grain size in the shear stress data mining method for the affected reach.	Fluvial audit Asset inspection records
Land use changes	Identify significant areas of land use change. Incorporate in rule-based approach following on from initial, national-scale model to flag locations where land use changes may	OS mapping Aerial imagery CORINE

Influencing factor	How to incorporate influencing factor	Data sets required
	influence the channel and its response to flood flows. Land use changes could potentially be factored in by editing the roughness values in the shear stress data mining model and rerunning the tool on a local (catchment) scale.	

7.6 Potential methods for incorporating influencing factors into the approaches on a national scale

This section outlines the spatial scale of the data sets considered in the preceding sections. It also considers the potential methods for incorporating the data sets into the approaches on a national scale. The section considers specifically whether identifying influencing factors, and incorporating them into the national methods, can be automated.

The data sets discussed in the preceding section (and in FRS17183/R1) are not all available on a national scale, and therefore they could only be incorporated into the national methods where they are available. For example, fluvial audit data ranges from catchment to sub-catchment scale. National scale data sets include:

- aerial imagery
- BGS drift/solid geology maps
- LiDAR
- OS mapping
- OS MasterMap
- flood asset data
- historic mapping
- CORINE
- records of channel maintenance

Catchment scale data sets include:

- fluvial audit

Local/reach scale data sets include:

- pre- and post-flood survey of sediment accumulation
- asset inspection records

The project has considered which data sets could be efficiently processed to create information on influencing factors to use in or alongside any national data on potential river channel change. This was not tested or explored in detail, however initial thoughts are presented in Table 6.5.

Table 6.5 Automating the process to identify influencing factors

Influencing factor	Data sets	Could it be automatically extracted from existing data? Y/ N / Maybe	Notes
Bedrock/valley confinement	Aerial imagery	Maybe	Valley confinement has been identified and extracted using GIS tools explored in report FRS17183/R3
	BGS geology maps	Yes	Geology maps are available as GIS layers and therefore coding could be used to identify areas of bedrock with lack of superficial geology or bedrock.
	Fluvial audit	Maybe	Fluvial audit data sets are not standardised. As a result, any coding carried out to extract the presence of bedrock and/or valley confinement would need to be adjusted for each audit.
Channel slope (natural)	LiDAR	Yes	There are readily available GIS coding routines available to extract slope data from LiDAR.
	OS mapping	No	Changing slope would need to be manually identified by reviewing contour lines.
Sediment supply and connectivity	Aerial imagery	No	The location of active sediments would have to be manually extracted.
	Fluvial audit	Maybe	Fluvial audit data sets are not standardised. As a result, any coding carried out to extract the presence of sediment supply and connectivity would need to be adjusted for each audit.
	Pre- and post-flood survey of sediment accumulation	Maybe	Surveys are collected on a site-specific basis, however, if a centralised database is established, then it may be possible to extract the location of sediment accumulation.
Magnitude, duration and sequencing of flows	Rainfall data	No	Manual processes would be required to review the hydrological data and identify changes in rainfall characteristics.
Large wood and riparian vegetation	Fluvial audit	Maybe	Fluvial audit data sets are not standardised. As a result, any coding carried out to extract the presence of large wood or riparian vegetation would need to be adjusted for each audit.
	Aerial imagery	No	Large wood would need to be manually identified from aerial imagery.
Flood plain infrastructure	Flood asset data	Yes	If asset data is in GIS formats specific types of flood plain infrastructure could be identified via an automated process.
	Fluvial audit	Maybe	Fluvial audit data sets are not standardised. As a result, any coding carried out to extract the

Influencing factor	Data sets	Could it be automatically extracted from existing data? Y/ N / Maybe	Notes
			presence of flood plain infrastructure would need to be adjusted for each audit.
	OS Mastermap	Maybe	The GIS layers separating different types of infrastructure would potentially allow this identification to be automated.
Channel modification	Historic mapping	No	Identifying channel modification from historic maps would have to be done manually.
	Aerial imagery	No	Channel modification would have to manually identified from aerial imagery.
	LiDAR	No	Channel modification would have to manually identified from LiDAR.
	Channel maintenance records	Maybe	Channel modifications could potentially be automated. If the records however, are not standardised this might require any coding to be adjusted for each record.
	Flood asset data	Yes	If asset data is in GIS formats specific types of flood plain infrastructure could be identified via an automated process.
Channel maintenance	Channel maintenance records	Maybe	Depending on the type of Environment Agency records, identifying channel maintenance could potentially be automated. If the records are not standardised, this might require any coding to be adjusted for each record.
	Fluvial audit	Maybe	Fluvial audit data sets are not standardised. As a result, any coding carried out to extract the presence of channel maintenance would need to be adjusted for each audit.
In-channel structures	Flood asset data	Yes	The shapefile format of asset data would allow the specific types of in-channel structures to be identified via an automated process.
	Fluvial audit	Maybe	Fluvial audit data sets are not standardised. As a result, any coding carried out to extract the presence of in-channel structures would need to be adjusted for each audit.
	OS Mastermap	Maybe	The GIS layers separating different types of in-channel structures would potentially allow this identification to be automated.
Asset failure	Fluvial audit	Maybe	Fluvial audit data sets are not standardised. As a result, any coding carried out to discover

Influencing factor	Data sets	Could it be automatically extracted from existing data? Y/ N / Maybe	Notes
			asset failure would need to be adjusted for each audit.
	Asset inspection records	Maybe	Depending on the type of Environment Agency records, identifying asset failures could potentially be automated. If the records are not standardised, this might require any coding to be adjusted for each record.
Land use changes	OS mapping	No	Land use changes would have to be manually identified from OS mapping.
	Aerial imagery	No	Land use changes would have to be manually identified from aerial imagery.
	CORINE	Yes	Identifying land use changes could be automated by using the GIS layers in CORINE.

The potential to automate the process of creating new data sets on each influencing factor and incorporating them will vary depending on the specific method (CAESAR-Lisflood or ST:REAM) and the data set being used. This is explored further below. It should be noted however, that as the methods are developed further, the ability to automate this process is likely to change over time.

In CAESAR-Lisflood a number of influencing factors could be incorporated into the method by an automated process by altering the DEM in the model. For example, in-channel structures such as weirs could be represented by modifying the bed elevation in the DEM and bedrock layer. A code could potentially be developed to raise the bed level of the DEM in the location of the weir polygon in GIS. This would require the weir height and dimensions to be included in an attribute table of the weir polygon, which would be used in the code to delineate the area of DEM modification. The adjusted DEM would then be bought into the modelling software as usual. The same could apply for flood plain infrastructure by modifying the DEM across the flood plain.

The model 'm' value (indicating run-off rates) and Manning's 'n' value could both be modified to account for land use changes. This could be automated if a GIS polygon of land use type included a representative 'm' or 'n' value in the attribute table, allowing the CAESAR-Lisflood software to read in a raster of spatially varying values. Adjusting the hydrological data in CAESAR-Lisflood would be more complex to automate but this could potentially be feasible, at least to partially automate.

In ST:REAM, the representation of bedrock is likely to require a manual process, linking the visual identification of bedrock to the spreadsheet inputs. However, where there is a GIS layer of bedrock reaches in fluvial audit data, automation may be possible. For incorporating large woody debris, flood plain infrastructure, channel modification and in-channel structures, the approach would involve the location of each feature and recalculating stream power to account for changes in channel dimensions and/or gradient. This process is expected to be manual, due to the need to interpret a variety of data sets and retrieve information on the potential adjustments of channel geometry, which would subsequently need to be applied to the stream power equation. For land use changes however, it is likely to be possible to automate this by using the CORINE GIS layer to update the CEH equation which calculates the QMED values of flow.

The majority of influencing factors would need to be manually represented for the half-yield method. For example, large woody debris, channel modifications and in-channel structures would all require an assessment on the impact on channel dimensions, which would then modify the inputs from the RHS data. This process would require someone to manually override the data being bought in from the RHS data set. Equally, to account for land use changes, the assessment of the impact on the flood response and potential adjustment of the daily flow gauge data would not be able to be automated.

For the shear stress data mining method, the majority of influencing factors would be difficult to account for due to the inability to update the model with specific information and rerun the underlying national scale model (that is, the risk of flooding from surface water complex model outputs). Therefore, the only variables that can be updated are sediment size and Manning's roughness. While land use changes and the presence of large wood and/or riparian vegetation could be represented, this would need a manual process. For example, for large wood and riparian vegetation, firstly the areas of large wood and vegetation need to be visually identified and assessed in terms of the extent of roughness created. Secondly, a GIS file of the spatially varying Manning's n values would be created and input into the data mining model. This sequence of tasks would not be possible as an automated process.

8 Climate change

8.1 Overview

Climate change is a main influencing factor that could potentially change the scale, nature and risk of flooding within river systems. This section briefly outlines the most up-to-date data sources in terms of climate change projections, and describes how climate change can be incorporated into the trialled methods.

8.2 Climate change and hydrological projections

The UK Climate Projections 2018 (UKCP18), published in November 2018, is the fourth generation of national climate projections for the UK and provides users with the most recent scientific evidence on projected climate changes. The projections are based on the latest developments in climate science and are the most comprehensive source of future climate information in the UK.

UKCP18 provides future climate projections for land and marine regions as well as observed (past) climate data for the UK. General climate change trends projected over UK land for the 21st century are broadly consistent with earlier projections (UKCP09), showing an increased chance of milder, wetter winters and hotter, drier summers along with an increase in the frequency and intensity of extreme weather.

UKCP18 comments that rainfall patterns across the UK are not uniform and vary seasonally and regionally and will continue to vary in the future. By the end of the century, UK winter rainfall is likely to be in the range +27% to -5% (low emission scenario) and +59% to -3% (high emission scenario).

UKCP18 on its own does not set out projected changes in hydrology, therefore further analysis is needed to derive hydrological projections. This work is ongoing through the joint research programme (Environment Agency, Making Use of the Latest Evidence on FCRM and Climate Change, SC150009).

8.2.1 Climate change allowances

Using Future Flows outputs for modelling the potential impact of climate change on river flows is an accepted method in UK water resources planning. The official Water Resource Planning Guidelines (Environment Agency, 2017) suggest using Future Flows to estimate potential future changes in source yields (at least for areas where demand does not outstrip supply).

Regional climate change allowances based on data from Defra research projects (Defra, 2009, FD2020 and Defra 2010 FD2648) were later developed to support flood risk management. Climate scenarios from UKCP09 are used to provide regional uplifts on peak river flows that can be applied to hydraulic modelling. These will continue to be used until new research updates operational practice. The guidance available online (Environment Agency 2019, https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances) provides peak river flow allowances which show the anticipated changes to peak flow by river basin district.

8.3 Incorporating climate change into the trialled methods

A description of how climate change is considered or could be incorporated into the methods shortlisted for this project is detailed here.

8.3.1 ST:REAM

ST:REAM outputs stream power imbalances between reaches in the form of quotients, in that the value is calculated by dividing the stream power of the reach in question by the stream power of the reach upstream. Consequently, any percentage increase applied to QMED to represent increased discharge under climate change would cancel out. This is demonstrated in the example calculation below in Figure 7-1. In addition, the method is not designed to account for extreme flows. Multiplying the QMED discharge by a climate change uplift factor, which is designed to be applied to extreme flows, is therefore likely to be highly ineffectual.

Investigations within this study found that SEPA has incorporated climate change flows into ST:REAM by applying a 20% climate change allowance increase to the QMED flow. Overall, the results were not found to be beneficial due to the limitations of the method described above.

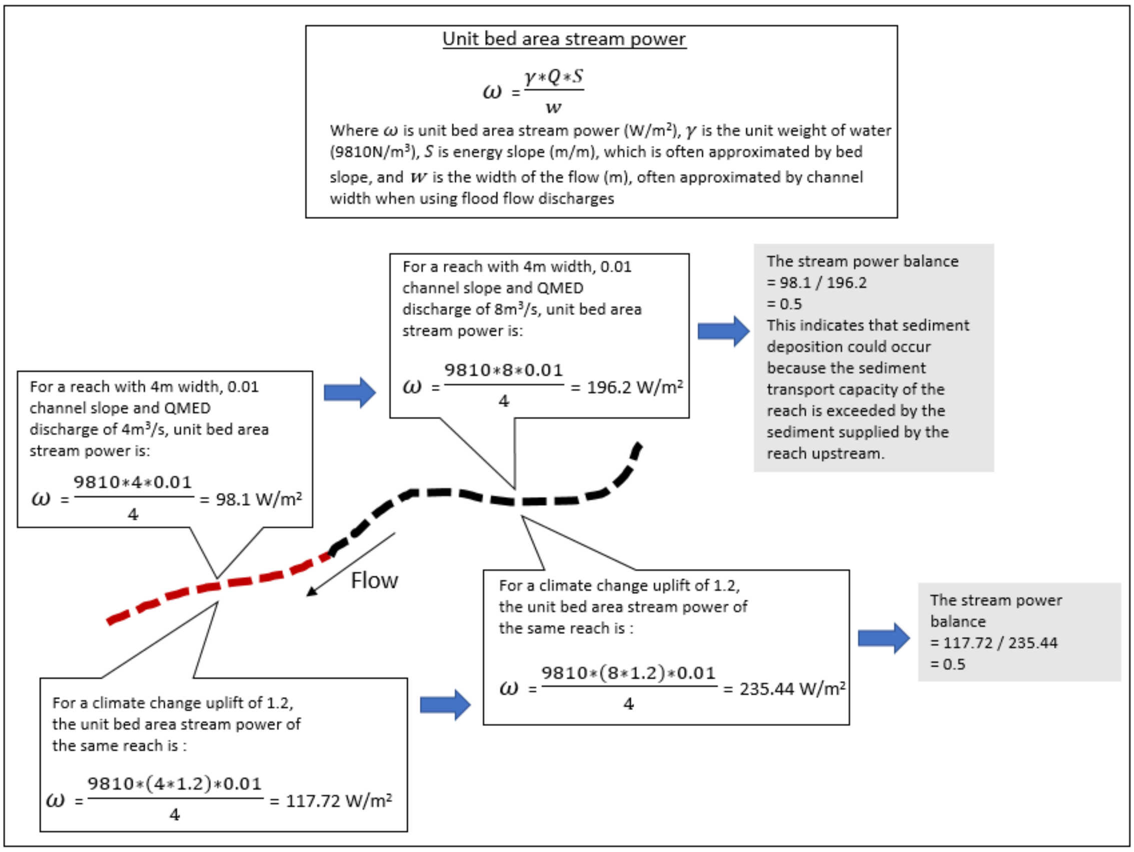


Figure 7-1 Example specific steam power calculation with climate change factors

QMED could potentially be adjusted for climate change by carrying out a specific hydrological assessment within multiple sub-catchments to generate a QMED for each reach. The hydrological assessment could be revised to represent changes in rainfall and the rainfall run-off relationship. Stream power ratios would change in ways reflecting the impacts of climate, vegetation and/or land-use changes within each sub-catchment. However, this would likely be very time consuming to apply at a national scale.

8.3.2 CAESAR-Lisflood

The effects of climate change can be incorporated into CAESAR-Lisflood by adjusting rainfall inputs according to climate change projections using the UKCP09 weather generator. UKUP09 presents 10,000 projections for 3 emission scenarios (low, medium, high) for 7, stationary 30-year climates, from 2020s (2010 to 2039) to 2080s (2070 to 2099). The weather generator is a statistical downscaling tool used to provide daily and hourly rainfall at spatial resolutions of 5 km^2. A detailed, step by step guide to using the UKCP09 weather generator is given in the UKCP09 User Interface manual.

The weather generator produces a user-defined number of random samples from possible future climates and provides a baseline equivalent for each of these results. The baseline situation should be derived from these scenarios, rather than from the long-term average historical climate, to ensure comparison with like-for-like data (Environment Agency, 2013). The minimum advised number of random rainfall series is 100 (for each emissions scenario and time period), although up to 10,000 can be generated to enable the range of uncertainty in the sampled data to be explored.

The UKCP09 weather generator user interface produces a zip file containing paired baseline and projected files, each containing hourly rainfall values for 30 years. These can be downloaded from the graphical user interface on the UKCP09 website. The baseline and climate change rainfall data can be used as the rainfall inputs for CAESAR-Lisflood by setting up and running a series of baseline and climate change scenarios.

This process is demonstrated by Coulthard and others (2012), who use UKCP09 probabilistic scenarios to adjust the rainfall inputs to CAESAR-Lisflood. The study uses the UKCP09 weather generator to simulate hourly rainfall for the baseline and climate change scenarios up to 2099. The adjusted rainfall inputs are used to drive the CAESAR landscape evolution model to simulate geomorphic change. The study reports that the impact of the increasing rainfall is amplified when translated into catchment run-off and, in turn, sediment yield, with a 100% increase in catchment mean sediment yield predicted between the baseline and the 2070 to 2099 high emissions scenario.

8.3.3 Half-yield

The flow duration curve is intrinsic to the method, incorporating the impact of the high magnitude, low frequency events. There is scope to adjust the flow regime to account for climate change by manipulating the flow duration curves using the outputs of the Centre for Ecology and Hydrology's Future Flows project. Future Flows used rainfall-run-off modelling techniques to estimate river flows under different climate scenarios based on UKCP09. The outputs are available free of charge for non-commercial use under licence agreement, and the use of Future Flows outputs for modelling the potential impact of climate change on river flows is an accepted method in UK water resources planning.

The use of Future Flows outputs in this project would focus on 2 specific data sets:

Future Flows hydrology

CEH modelled river flow time series for 282 gauged locations in the UK, spanning the period from 1951 to 2098 and reflecting the progressive impact of climate change on river flows based. For any gauged locations that are relevant within the context of this project, the relevant time series will be analysed to inform flow duration curves that represent the impacts of climate change.

Regional changes in river flow

A 'change factor' is essentially the percentage difference between the flow now and that which would be expected for a future reference climate, accounting for possible changes in the hydrological regime that would occur as a result of climate changes. For each modelled river, the Future Flows project provided change factors for different flow percentiles based on a 2050 horizon. The project compared the predicted flows for the future with those occurring now, expressing the differences in percentage terms. Change factors are available for Q10, Q30, mean flow, Q95 for example. Change factors do vary spatially. In a region or river basin, a range of change factors are observed, however rivers that are close to each other and have similar characteristics do see very similar change factors. A donor approach in which modelled change factors are borrowed from a nearby similar river can therefore be adopted, allowing climate change to be accommodated in flow duration curves derived for ungauged sites.

A trial was carried out to test the half-yield method with climate change flows. This is presented in Appendix E. The half-yield method was chosen to be used as the trial climate change run since this method had not been previously trialled by other research.

8.3.4 Shear stress data mining

Climate change cannot be incorporated directly into this method as the underlying data is only available for 3 annual exceedance probabilities (AEP) (3.33%, 1% and 0.1%). However, a series of sensitivity maps can be generated to assess how the potential for erosion changes with increased rainfall. This can then be used to simulate climate change.

The method can be applied for the 3 AEPs for which there are depth and velocity grids. Following an analysis of the changes in total rainfall used to derive the map outputs for the 0.1%, 1% and 3.33% AEP events, it was found that the difference in total rainfall in the 1% to the 0.1% AEP was large (>100%), but that the change between 3.33% and 1% AEP rainfall totals was approximately 40% higher. This is similar to the projected rainfall intensity uplifts for 2080 in the climate impact tool and the projected UKWIR rainfall increases (UKWIR, 2017).

Therefore, comparing the SSDM outputs for the 3.33% and 1% AEP can give an estimate of the potential sensitivity of spatial distribution of erosion and deposition to increased rainfall, and can be used to simulate the impacts of climate change. This is further explained in FRS17183/R4.

9 Method trials – main learning points

9.1.1 Overview

This section outlines the main learning points from the trial phase of the project. Further detail is provided in Appendix F, including:

- recommendations if a method is used nationally
- technical recommendations to improve the method setup
- technical lessons learnt
- limitations and benefits for use

9.1.2 ST:REAM

The following list summarises the main lessons learnt during the ST:REAM trial phase:

- The main data sets required for ST:REAM are readily available and mainly open source (this means they do not requiring licensing).
- Results provide a good understanding of catchment scale processes, however the method may not be appropriate for all types of river. For this reason, accurately modelling geomorphological processes is expected to vary across catchments. This was illustrated by the varying success rate across the 3 catchments within the method trial when comparing method results to fluvial audit data (13 to 60% success rate).
- The ST:REAM method cannot predict lateral geomorphological processes and rates of erosion/deposition.
- Testing in Scotland by SEPA has shown it is feasible to create a national scale model. However, the trial phase of this project has shown that this would mean hard work, including creating the correct topology/relationship of the river branches in all catchments in the UK. Analysis and verification would be needed at the catchment scale, which would require more time and resources.
- Certain elements of the method setup require manual checks to ensure consistency (that is, where automated processes have failed). This is likely to be time consuming when modelling on a national scale.
- In terms of modelling climate change, attempting to crudely uplift the QMED flows is unlikely to be successful. However, a detailed hydrological analysis could be carried out at the catchment scale, providing revised QMED values to represent different climate change scenarios. This is expected to be a time-consuming process to carry out nationally.

9.1.3 CAESAR-Lisflood

The following list summarises the main lessons learnt during the CAESAR-Lisflood trial phase:

- Not all data sets are readily available and some complex data sets are needed (for example, hourly rainfall, grain size data and flow gauging). However, the level of complexity incorporated into each model is user-defined (that is, a coarse resolution, simple basin model could be developed with minimal data needs).
- Model outputs illustrate good potential to predict geomorphological processes, providing rates of accumulation and net erosion/deposition. The model also incorporates sediment inputs from valley slopes and simulates lateral erosion processes, which allows long-term morphological changes such as landform evolution and channel avulsion to be predicted. This level of detail would potentially be very useful as an asset management planning tool.
- In terms of comparing model predictions of geomorphological processes against fluvial audit data, the results were shown to have a 50% success rate in the Kent catchment. Some of the inconsistencies were related to the coarse resolution of the LiDAR data, which did not represent the current (modified) course of the channel. Modelling results were therefore offset from the existing channel location. This has highlighted the essential need for model validation and sensibility checks of the results using local geomorphological knowledge. The benefits of using a higher resolution DTM is also highlighted.
- National scale modelling would be possible by developing individual basin models at a catchment scale and compiling the outputs into one national data set. However, this is expected to be resource and time intensive, requiring adequate computing infrastructure (cloud computing), multiple teams of hydraulic modelling specialists and local geomorphological knowledge to sensibility check the model outputs. Due to the user-defined nature of the model parametrisation and setup, there is a risk that a different model development approach could be applied between the multiple modelling teams, leading to inconsistencies in modelling outputs between each individual basin model.
- CAESAR-Lisflood can incorporate climate change by adjusting the rainfall inputs according to climate change projections using the UKCP09 weather generator. This has been tested in a study by Coulthard and others (2012) in the River Swale catchment in Yorkshire.

9.1.4 Half-yield method

The following list summarises the main lessons learnt during the half-yield method trial phase:

- The main data sets required are readily available (DRN and RHS), however this method's reliability on the coverage and accuracy of the RHS data is a major limitation.
- The ability to predict geomorphological processes is shown to have a high success rate (75 to 100% success rate in matching fluvial audit data in trials) when ignoring the locations where no RHS survey data is available, demonstrating the accuracy of the tool to provide locally detailed data. However, when accounting for the absence of the RHS survey data points, the agreement rate between model outputs and fluvial audit data reduces significantly (38 to 50%).
- Predicting lateral geomorphological processes and rates of erosion/deposition are also beyond the ability of the half-yield method. In addition, since outputs are generated at individual cross sections, with often extended reaches with no data points, the approach does not simulate spatial linkages in sediment movement between reaches. Reach-scale processes could therefore easily be missed.

- In terms of the ability to generate a national scale model, this is shown to be feasible by modelling at a catchment scale and integrating the outputs into a national level data set. Batch processing can be carried out, increasing the efficiency of running multiple simulations. However, the RHS survey data is sparse in some locations, so until this data coverage and quality is improved, there is likely be incomplete coverage nationally.
- Incorporating climate change into the method is feasible, by manipulating the flow duration curves through the use of the Future Flows data set (for gauged catchments) and 'change factors' (in ungauged catchments). At a national scale, it is recommended using the 'change factors' methodology due to national scale coverage.

9.1.5 Shear stress data mining method

The following list summarises the main lessons learnt during the shear stress data mining method trial phase:

- This method needs very little data and the required data sets are readily available.
- The preliminary investigation of this method within the Kent, Stour and Wharfe catchments illustrated a good potential for the model to predict geomorphological processes, by comparing to fluvial audit data and aerial imagery. The spot check comparisons showed a good correlation with audit data at a fine resolution (2 m), while the outputs also corroborated data at the reach-scale and valley scale. A few limitations were identified and include the reduced accuracy of model outputs in areas of tree cover, as well as within lower catchment reaches.
- The method cannot predict net erosion or deposition rates, however there is the potential to identify areas of channel migration (through lateral erosion). The method could potentially be very useful as an asset management planning tool, however further investigations would be needed to improve results interpretation (for example, majority filtering to remove isolated points of data/rapid spatial variations, as well as removing woodland).
- The model is run nationally, so no model upscaling would be needed. It is also easy to run nationally at a fine resolution, with a single run possible overnight. The initial model simulations used a single assumption on D50 sediment size, Manning's roughness and Shield's constant. Further trials were carried out to develop a scenario library of outputs using a range of different parameters. This will allow further user testing and validation, whereby the results based on the most appropriate local conditions can be selected from the library. This is further explained in FRS17183/R4.
- The data mining method cannot fully account for climate change since the model is applied nationally, preventing regional forecast uplift factors being applied. However, by comparing the 3.33% AEP and 1% AEP flood event outputs, it is possible to assess the sensitivity of modelling predictions to increases in rainfall.
- Further tests were carried out to address some model limitations and provide a pilot national data set for England and Wales, which can be used for further validation and user testing. This is described in FRS17183/R4.

10 Developing national scale information on river channel change

10.1 Using national scale methods to identify hotspots of change

Currently, there are no national data sets available that show the likelihood or risk of geomorphological change in England and Wales.

Based on the findings of the trial phase of the project, national channel change methods can be used to identify the dominant process of sediment erosion, deposition or transfer, showing a potential for river channel change.

If combined with analysis of factors that can influence the scale and rate of these processes (for example, sediment supply), the likelihood for change can be identified. Further analysis, such as detailed hydraulic modelling or comparison against national flood maps could identify potential consequences of these changes (for example, the presence of infrastructure near to areas of erosion or the build-up of sedimentation in flood-prone areas).

The risk of morphological change could be categorised in terms of low, medium or high based on the likelihood of change and the consequences of that change (just like in flood risk mapping).

The national flood risk assessment, published as the Risk of Flooding from Rivers and Sea map (Environment Agency), uses this approach and also has results that show how suitable the results are at given spatial scales. The suitability scale is based on how well the computer flood model performs and how good the input data is in that location. Crucially, local experts review this information and change results where they have better local data. A similar suitability scale could be applied to the results of national scale river channel change modelling.

Areas that are classified as high risk in terms of likelihood and consequences of geomorphic activity should help to target more detailed analysis.

A map or data set of river channel change hotspots, showing the likelihood and consequences of change nationally could be produced as a first step to understanding how sensitive rivers in England and Wales are to geomorphological change. Some work to progress this was carried out using the shear stress data mining method.

10.1.1 Potential approach - hierarchical assessment

There could be several ways of combining the data from the national models, influencing factors and receptors to identify hotspots of river channel change.

One approach could be to use a hierarchical assessment framework, as illustrated in Figure 9-1.

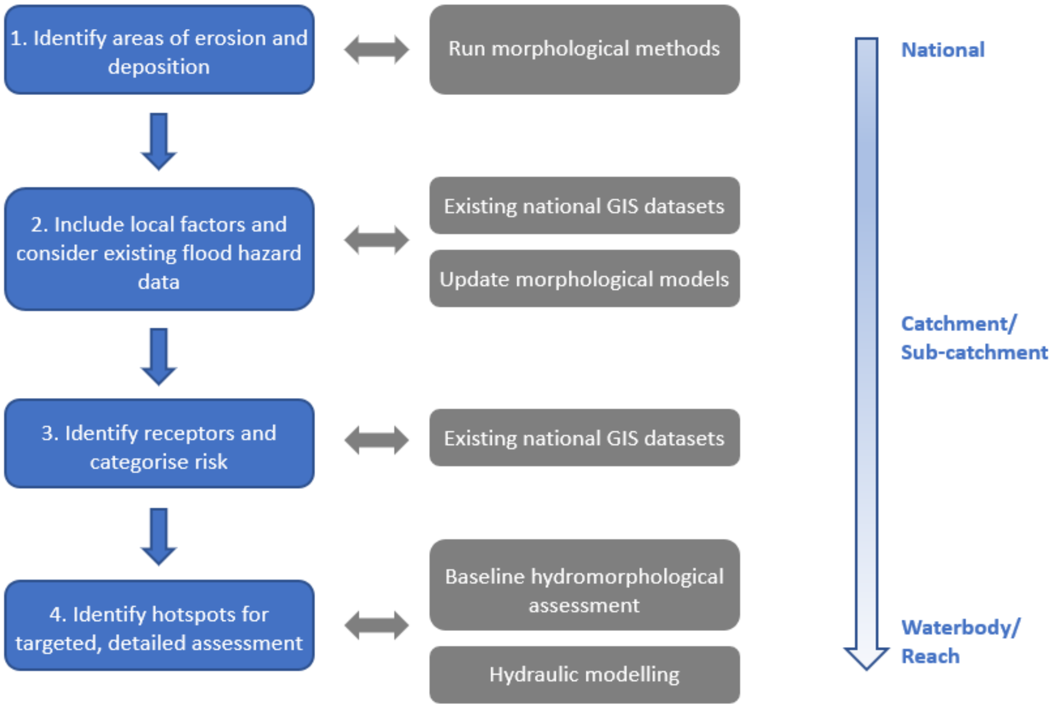


Figure 9-1 Hierarchical assessment framework for integrating morphological change into flood risk management

At a national level, morphological methods (such as some of those trialled in this project) could be used to identify areas where erosion and deposition could occur.

Next, existing data sets could be analysed to identify the presence of influencing factors on river channel change (as described in FRS17183/R2). Influencing factors can also be incorporated into the morphological methods (where they are not already included as part of the main method inputs). Existing national flood hazard data can be examined to determine where potential changes in flood risk could occur.

To improve flood risk mapping, the method outputs would need to be combined with receptors in the flood plain such as infrastructure, services and property to fully understand the likelihood and consequences of channel change. The risk of morphological change could be categorised, for example, as low, medium or high, as well as an indication of confidence in the results. This would need to be reviewed and adjusted based on local knowledge, where necessary.

An illustrated example of the process is given in Figure 9-2.

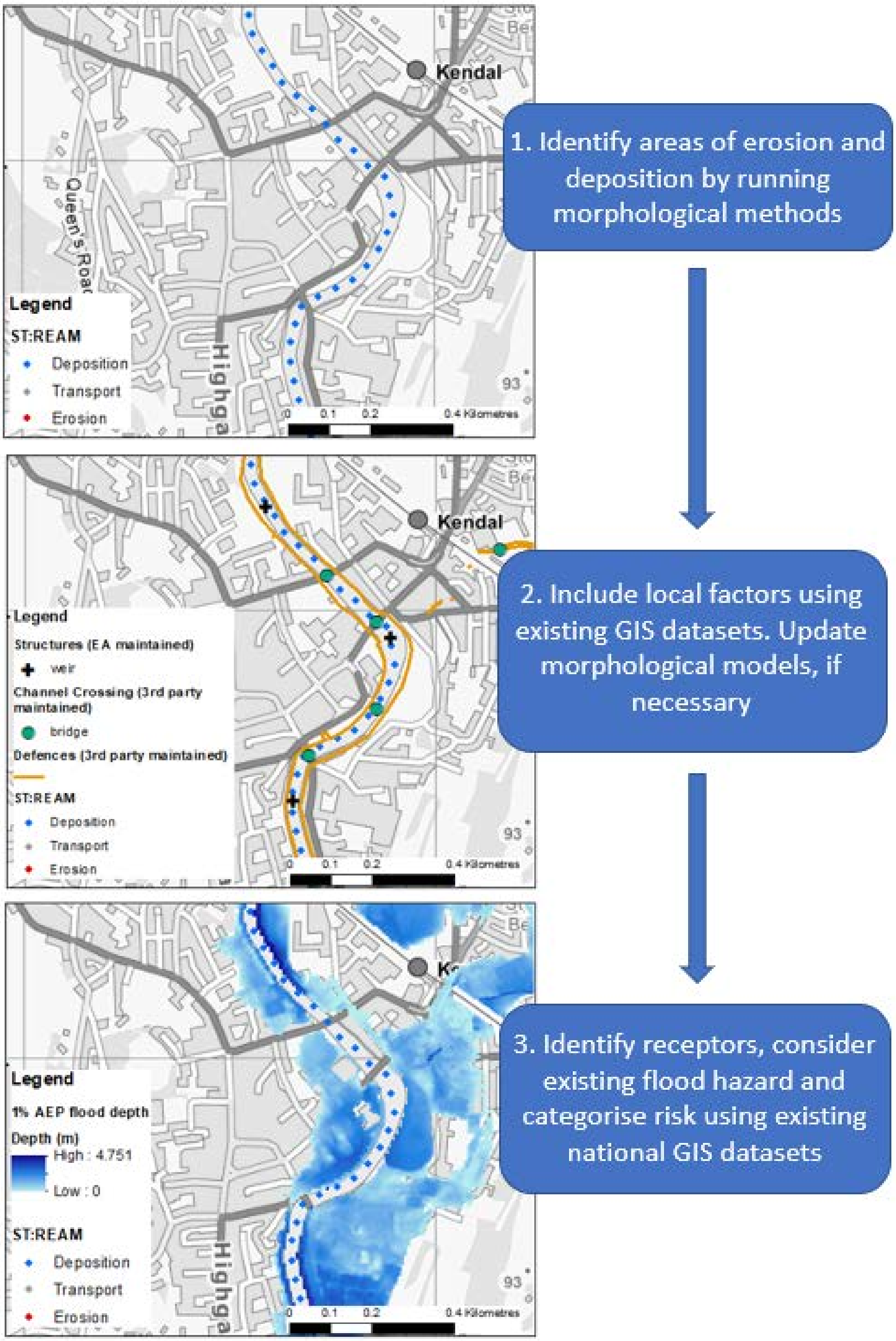


Figure 9-2 Illustrated example of how the national models, influencing factors and flood hazard data can be used to prioritise more detailed investigations

In the example, the outputs from ST:REAM are used to identify a depositional reach through the centre of Kendal (top image). Influencing factors are consulted (middle image), using national GIS data sets. In this case, Environment Agency asset data is used to identify structures are within the reach. These include weirs, bridges and flood defences. The weirs have the potential to decrease the bed gradient locally by trapping sediment, and therefore the reach could be flagged as a potential location for channel change, in terms of sedimentation. Stream power calculations within ST:REAM could be recalculated for the reach if it felt that the impact of the weirs on the channel slope is not well represented within the ST:REAM model. The national flood hazard data (bottom image) shows that in a 1% AEP flood, the third party flood defences are overtopped and there is significant flooding throughout the urban area. There are significant numbers of receptors within the flood plain (properties and infrastructure).

The additional work carried out for the shear stress data mining trial (FRS17183/R4) and for assessing the influence of valley confinement (FRS17183/R3) looked further at how risk maps of river channel change could be created.

Areas that are classified as high risk in terms of the likelihood and consequences of morphological change are those where more detailed analysis should be targeted. Detailed assessments could take the form of baseline geomorphological assessments and hydraulic modelling studies.

Baseline geomorphological assessments

A baseline geomorphological assessment provides an understanding of the dynamic fluvial geomorphology of the river system, providing vital 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. It also supports the selection of an appropriate modelling tool that can predict the (annual to decadal) response of river beds and banks to assess the flood vulnerability (Nones, 2019).

Hydraulic modelling studies

Hydraulic models can be created to quantify how flood hazard will be impacted by changing channel capacity using sensitivity testing on physical change such as alterations to width, roughness, or depth from sedimentation (see Appendix A). Hydraulic flood modelling can be carried out to determine potential flood impacts under a variety of flows (for example, climate change scenarios) and channel sizes. These models can be reviewed and updated, if necessary, following major flood events and during scheme designs.

Selecting the most appropriate hydraulic modelling method for predicting channel change depends on the timescale and spatial scale of the problem under investigation. At a catchment scale 1D or 2D modelling approaches are most likely to be appropriate. At smaller, reach scales, localised problems such as bridge scour could be addressed with more detailed modelling approaches such as 3D or dynamic sediment modelling.

Hydraulic modelling, carried out locally, can be used to identify if gravel accumulation is causing an increase in flood risk using regular monitoring and setting trigger levels, whereby the gravel would need to be removed.

These assessments and studies can be resource intensive and costly, so targeting them where they are needed (for current and future climates) could create resource efficiencies.

10.1.2 Potential approach – decision support framework

The research showed that each of the methods trialled had merits and pitfalls. A potential way forward could be to combine national strategic scale and detailed hydraulic model results and use them where they are best applied.

Data from the individual methods and the influencing factors data sets could be brought together in a decision support framework. This is an information framework that supports decision-making activities and facilitates organisational processes.

The user would define their problem and required outcome, then use the decision support framework to select which of the national scale methods and supporting data sets to use to help inform that decision (Figure 9.3). This would enable the user to select the methods and data most suited to their catchment type, location and particular river management problem.

Figure 9.3 Using a decision support framework to select the most suitable method of predicting river change

10.2 Initial testing to gather user needs

A user workshop was held in May 2019 to present the method trial findings to representatives from flood and coastal risk management. The workshop also provided an opportunity to better understand how the Environment Agency may use national mapped data of river channel change (hotspots of locations susceptible to erosion and deposition, and/or geomorphological change risk maps).

The workshop provided a valuable insight into the types of data on river channel change that is used in which operational processes. At the workshop the research team gathered feedback on how staff would use hotpot/risk map data for which operational processes, and their requirements for this data to inform any future development. Details of the workshop's findings are provided in Appendix G.

Many teams across the Environment Agency currently use a range of channel change data sets at both strategic national scale as well as for local reach scales. The uses encompass 'business as usual' as well as incident planning and response.

Information and knowledge on channel changes is often provided by local experts on an ad hoc basis. Some guidance and data exists where gravel management is happening, but the data is often not shared or stored centrally, limiting access and use by others. Historic records are not accessible and there is no national survey archive for channel changes.

The workshop found there is no nationally integrated data exchange, storage and access concerning channel change and sediment management.

The user group examined the methods trialled through this research. Based on their understanding of the methods shared at the workshop, ST:REAM was the preferred approach, followed by the shear stress data mining method.

ST:REAM was considered to be a good high-level tool to identify potential 'at risk' locations from channel change. There is also less need for local quality assurance testing due to the broad scale modelling outputs, although some validation of any national data set would be recommended. In this sense, there were some concerns raised about the high resolution outputs produced by the shear stress data mining method and CAESAR-Lisflood and publishing local scale data with a high level of detail. This would require local validation, which would be time consuming and resource intensive. In comparison, most of the group was comfortable with presenting the outputs of ST:REAM at a strategic level, with further detail being added using local knowledge.

The user group agreed that understanding how rivers function and react can help to build resilience in flood risk management operations, particularly for working more with natural processes.

At the local, catchment and national scales such data could underpin decisions for catchment management, including asset and channel maintenance, location of natural flood management schemes, incident planning response in at risk locations, and for risk assessment to determine future investment needs.

Risk management that is planned and prepared for the future, prioritised to locations with greatest risk or opportunity, and that carries out maintenance or adaptation sustainably can provide revenue and capital savings in the long term.

A summary of the potential uses and benefits of river channel change data for flood risk management is provide in Table 9.1.

Table 9.1 Automating the process to identify influencing factors

Topic	Potential uses and benefits of river channel change data for flood risk management
Create resilient places	• Create new innovative data on river channel change to support the ambitions of the National Flood and Coastal Erosion Risk Management Strategy for England and 25 Year Environment Plan goals • Fills key evidence gap about natural processes to inform how we can work with nature • Infrastructure and natural systems could be more resilient to a future climate • Inform pipeline development of capital schemes and restoration plans
Decision support	• Local uses, for example, where channel maintenance could be best targeted (before or after floods) • Catchment uses, for example, how best to locate and design natural flood management and restore natural systems • National uses, for example, future risk management and investment in channel maintenance
Potential benefits	• More efficient and cost effective practices if: • channel management works with natural processes • risk management informed and prepared for future change • activities are targeted to most sensitive areas (maintenance and modelling)

The group concluded that risk categories or information showing the impact of change would be needed for the data to be useful to local and national flood risk management operations. This needs to be supported by guidance on how to use the data.

The next step for this research could be to pilot a decision support framework or hierarchy that combines one or more trialled methods with data on influencing factors and impacts to create hotspot and risk maps. These could be tested by operational staff to see how it would be used in practice, before any national data set and process is implemented.

10.3 Potential to use hotspot maps for sustainable channel management strategies

Understanding the processes operating in a reach, within the wider context of its catchment, can help to develop sustainable channel management strategies, particularly those that would work with rather than against natural processes.

For example, data on hotspots of river channel change could be used to identify where to best protect and restore the natural function of catchments, a requirement of the national flood and coastal erosion risk management strategy (Environment Agency, draft 2019) and the 25 Year Environment Plan (Defra, 2018).

Working with natural processes aims to protect, restore and emulate the natural functions of catchments, flood plains, rivers and the coasts (Environment Agency, 2012). In terms of rivers, this can include sustainable channel management techniques such as restoring functioning flood plains, restoring rivers and removing redundant in-channel structures, installing or retaining large woody material in river channels and managed realignment. This would enable river and channel management to work with morphological change to have positive impacts on the river system. Other strategic factors to consider when managing channels include understanding pathways of sediment and key sites where change is most likely, historic change, and river type and likely future trajectory.

In the channel management handbook (Environment Agency, 2015), good channel management is defined as:

> *"a course of action that achieves the needs of humans for flood risk and/or land drainage purposes, that has due regard of the needs of ecology and wildlife. In some situations, this can be met by allowing natural channel-forming processes to establish."'*

Sustainable channel management strategies should recognise that:

- the river and flood plain are a single unit
- connectivity must be viewed both downstream and cross valley
- there is a wider process-form linkage throughout the river system. Management strategies should work with the river, rather than against it. Management strategies developed from an isolated site perspective must be avoided
- change is inevitable and management strategies should not work against this

River channel change data can help flood risk management staff understand which areas are most susceptible to erosion or deposition under normal and extreme flows to allow management strategies to work with the natural river processes. This can help to develop sustainable routine and intermittent maintenance programmes, including gravel management at a multi-reach scale, and to identify river restoration opportunities.

11 Conclusions

11.1 Overview

The research aimed to test and evaluate methods to identify in-channel geomorphological activity nationally across England and Wales in normal and extreme flows.

A literature review and multi-criteria analysis was used to identify and shortlist the following 4 methods to take forward for testing:

- ST:REAM
- CAESAR-Lisflood
- Half-yield method
- Shear stress data mining method

A review of available data, a multi-criteria analysis and advice from the project steering group was used to identity and shortlist 3 catchments covering 3 environmental settings within which to test the methods during the trial phase:

- River Kent, Cumbria (upland)
- River Wharfe, North Yorkshire (upland-lowland transitional)
- River Stour, Dorset (lowland)

11.2 Trial phase: results validation

The trial phase involved applying the methods to the test catchments, enabling the project team to gain a comprehensive understanding of the strengths and weaknesses of the methods in practice.

Based on the results of the trial phase and validation, none of the results are accurate enough to provide a basis for assessment alone. The level of inaccurate results (>50% in many cases) could potentially lead to misleading conclusions about how reaches behave and could not be used as the basis for channel management.

Further trials are needed using the findings and lessons from this research. The research has started this with a national pilot of the shear stress data mining method.

Any data used for operational flood risk and environment management needs to take into account influencing factors on channel change and be validated against actual records.

11.3 Main outcomes

11.3.1 Ability to predict geomorphological processes

ST:REAM

The trial phase results show that ST:REAM provides a good understanding of catchment scale processes. However, the methodology is predicted not to be appropriate for all types of river, and therefore the ability to accurately model geomorphological processes is expected to vary across catchments. This was illustrated by the varying success rate across the 3 catchments within the method trial when comparing method results to fluvial audit data (13 to 60% success rate).

The ability to model local scale detail is considered to be limited for the majority of the influencing factors identified in Report 1. This is due to local scale variability (for example, within a 50 m river reach) needing to be extreme in order to influence overall reach scale values of sediment transporting capacity.

CAESAR-Lisflood

The model outputs illustrated a reasonably good potential to predict geomorphological processes, providing net erosion/deposition. The model also incorporates sediment inputs from valley slopes and simulates lateral erosion processes, which allow long-term morphological changes such as landform evolution and channel avulsion to be predicted. This level of detail would potentially be very useful as an asset management planning tool. In terms of comparing model predictions of geomorphological processes against fluvial audit data, the results were shown to have a 50% success rate in the Kent catchment. Some of the inconsistencies were related to the coarse resolution of the LiDAR data, which did not represent the current (modified) course of the channel.

Of the 4 methods trialled, CAESAR-Lisflood lends itself well to incorporating influencing factors within the model setup. CAESAR-Lisflood was run in catchment mode for the trial phase of this project, using rainfall data. It is also possible to run the model in reach mode, which would make it possible to explore spatially detailed influencing factors. This could include, for example, a series of in-channel wood jams, channel dredging, and asset failure, such as the collapse of bank protection or weir failure.

Half-yield method

The ability to predict geomorphological processes is shown to heavily rely on the location, availability and accuracy of RHS data. When available, the method has a high success rate (75 to 100%) in matching fluvial audit data in trials, demonstrating the accuracy of the tool to provide locally detailed data. However, when accounting for the absence of the RHS survey data points, the agreement rate between model outputs and fluvial audit data reduces significantly (38 to 50%).

The half-yield method is not suited as well as ST:REAM to incorporating influencing factors. This is due to its cross section approach, which does not account for overall reach conditions.

Shear stress data mining method

The preliminary investigation of this method within test catchments illustrated a good potential for the model to predict geomorphological processes by comparing results with fluvial audit data and aerial imagery. The spot check comparisons showed a good correlation with audit data at a fine resolution (2 m), while the outputs also corroborated data at the reach and valley scale. A few limitations identified include the reduced accuracy of model outputs in areas of tree cover, as well as within lower catchment reaches.

Many influencing factors would be difficult to account for due to the inability to update the model with specific information and rerun the underlying national scale model (that is, the risk of flooding from surface water complex model outputs). The only variables that can be updated are sediment size and Manning’s roughness. However, as with the other models, separate data sets could be used together to identify the likelihood and impact of river channel change.

11.3.2 Ability to include climate change

ST:REAM

ST:REAM outputs stream power imbalances between reaches in the form of quotients, that is the value is calculated by dividing the stream power of the reach in question by the stream power of the reach upstream. Consequently, any percentage increase applied to QMED to represent increased discharge under climate change would be cancelled out. In addition, multiplying the QMED discharge by a climate change uplift factor, which is designed to be applied to extreme flows, is likely to be ineffectual. Due to these 2 factors, the potential to incorporate climate change into the ST:REAM method is limited. A detailed hydrological analysis could be carried out at the catchment scale, providing revised QMED values to represent different climate change scenarios. However, this is expected to be time-consuming on a national scale.

CAESAR-Lisflood

The effects of climate change can be incorporated into CAESAR-Lisflood by adjusting rainfall inputs according to climate change projections using the UK Climate Projections 2009 (UKCP09) weather generator. The weather generator is a statistical downscaling tool used to provide daily and hourly rainfall at spatial resolutions of 5 km^2. The relevant files can be downloaded from the graphical user interface on the UKCP09 website. It is therefore relatively easy to incorporate climate change into the CAESAR-Lisflood method, as demonstrated by Coulthard and others (2012).

Half-yield method

There is scope to adjust the flow regime to account for climate change by manipulating the flow duration curves which are intrinsic to the method. This could be achieved by using the outputs of the Centre for Ecology & Hydrology's Future Flows project. Using Future Flows outputs to model the potential impact of climate change on river flows is an accepted method in UK water resource planning.

Shear stress data mining method

The shear stress data mining method cannot fully account for climate change. However, comparing the 3.33% and 1% annual exceedance probabilities could give an estimate of the sensitivity of the spatial distribution of erosion and deposition potential to increased rainfall.

11.3.3 Ability to scale to a national level

ST:REAM

The work carried out by SEPA in Scotland has shown that it is feasible to create a national scale model. The trial carried out for this project has verified that ST:REAM could be used to create this model, but it has highlighted that analysis and validation would be needed at a catchment scale, increasing the time needed.

CAESAR-Lisflood

National scale modelling using CAESAR-Lisflood would be possible, by developing individual basin models at a catchment scale and compiling the outputs into one national data set. However, this is expected to be resource and time intensive, requiring adequate computing infrastructure (cloud computing), multiple teams of hydraulic modelling specialists and local geomorphological knowledge to sensibility check the model outputs. The level of detail incorporated in model parameterisation can be user-defined, which would alter the time and resource requirements.

Half-yield method

The trial carried out for this project has verified that it would be feasible to generate a national scale model, by modelling at a catchment scale and integrating the outputs into a national level data set. Batch processing can be carried out, increasing the efficiency of running multiple simulations. However, the RHS survey data is sparse or not available in some locations, meaning this is likely to result in incomplete coverage nationally.

Shear stress data mining method

The model is run at the national scale, so no model upscaling would be needed. It is also easy to run nationally at a fine resolution, with a single run possible overnight. However, the current model simulations use a single assumption on D50 sediment size, Manning's roughness and Shield's constant, so a scenario library of outputs using a range of different parameters should be used to select an appropriate output for local conditions. Potential limitations need to be addressed (such as reduced accuracy in lower catchment reaches) and further improvements are needed to refine method outputs (such as majority filtering and removing woodland).

11.3.4 Creating national risk maps of river channel change

Currently, there are no national data sets available that show the likelihood or risk of geomorphological change in England and Wales.

Based on the findings of the trial phase of the project, national channel change methods can be used to identify the dominant process or sediment erosion, deposition or transfer; showing a potential for river channel change.

If combined with data that can indicate where channel change is more likely (based on factors that influence the scale and rate of these processes such as sediment supply), the likelihood for change can be identified. Further analysis, such as detailed hydraulic modelling or comparison against national flood maps, could identify potential consequences of these changes (for example, the presence of infrastructure near to areas of erosion or the build-up of sedimentation in flood-prone areas).

The risk of morphological change could be categorised in terms of low, medium or high risk based on the likelihood of change and the consequences of that change (just like in flood risk mapping).

This could be achieved using a hierarchical approach or a decision support framework.

Having consistent, national scale data on river channel change can help flood risk management staff to:

- understand which areas are most susceptible to erosion or deposition, under normal and extreme flows
- develop routine and intermittent maintenance programmes that work with natural processes
- identify river restoration opportunities
- develop gravel management at a multi-reach scale

11.3.5 Recommendations

It is recommended that the methods are further validated and further user needs analysis is carried out before a method is selected to provide national scale information on river channel change.

If approaches such as ST:REAM and the shear stress data mining method (that are based on a single value on a hydrograph) are further validated, further research may be required. Specifically for investigating how to include feedback within the model so that potential erosion on the rising limb of the hydrograph and deposition on the falling limb is accounted for.

The data analysis used for this research was limited by the lack of observed flood impact data in the trial catchments. The research tested the models in 3 catchments. Before any maps or modelled information on river channel change are used as part of flood risk and environment management, the maps would need to be validated in other catchments. It is recommended that any future work in additional catchments compares the model outputs with available on-the-ground, observed flood data to highlight where any limitations within the modelling occur and investigate potential adjustments to the models.

To support this, changes in river channels could be monitored over time and further evidence of change during both normal and extreme flows could be collected. This will help to provide evidence to validate any modelled data produced in the future.

There are benefits of taking this research forward to carry out a national assessment of likely behaviour using the simpler models and data that accounts for influencing factors like sediment supply and confinement. This could be combined with existing information so that risk of change, its impacts and opportunities could be identified.

This can be used for informing resilient and sustainable channel maintenance, and more complex modelling for targeted site-specific investigations.

Further work is also recommended to understand how national hot spot maps would be used. Any new mapped information would need to be supported with appropriate guidance for interpreting and using them.

11.3.6 Next steps

Developing the method outputs to make sure that they are as useful as possible so users can improve their business processes is an important next step.

The next step for this research could be to pilot a decision support framework or hierarchy that combines one or more trialled methods with data on influencing factors and impacts to create hotspots and risk maps. Guidance on how to use the data would need to be developed.

These could be tested by operational staff to see how they would be used in practice, before any national data set and process is implemented.

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List of abbreviations

AEP	Annual exceedance probability
AGE	Annual geomorphic energy
BGS	British Geological Survey
CCRA	Climate change risk assessment
CEH	Centre for Ecology & Hydrology
CES	Conveyance Estimation System
CFD	Computational fluid dynamics
CORINE	CORINE (Land Cover) 'coordination of information on the environment'
CSR	Capacity supply ratio
DA (grid)	Drainage area (grid)
Defra	Department for Environment, Food & Rural Affairs
DEM	Digital elevation model
DRN	Digital river network
DTM	Digital terrain model
FDC	Flow duration curve
FME	Feature Manipulation Engine
GIS	Geographic information system
IHM	Integrated height model
LEM	Landscape evolution model
LiDAR	Light Detection and Ranging
MCA	Multi-criteria analysis
NRFA	National River Flow Archive
OS	Ordnance Survey
QA	Quality assurance
QMED	Median of the annual maximum discharge time series
REAS	River Energy Audit Scheme
RHS	River Habitat Survey
SEPA	Scottish Environment Protection Agency
SRES	Special Report on Emissions Scenarios
ST:REAM	Sediment Transport: Reach Equilibrium Assessment Method
UKCP	UK Climate Projections
UKWIR	UK Water Industry Research
VBA	Visual Basic for Applications

WFD	Water Framework Directive
W/m	Watts per metre

Appendix A: Reach scale hydraulic modelling examples

Hydrodynamic modelling is a type of simulation using in-channel/flood plain elevation data and hydrograph inflows, where flow varies over time. Hydraulic modelling is an important tool for determining flood hazard and flood risk at the local scale.

Examples are provided below to describe hydrodynamic models and geomorphological assessment methods that have already been used in the Environment Agency to understand local impacts of channel change on flood hazard (discharge, flood extent, velocity, depth, and probability of flooding).

A1 Case study: Swindale Beck

In a study carried out by JBA Consulting on a 2 km stretch of the Swindale Beck (tributary of the River Eden) in Cumbria, a desk based hydromorphological assessment and site walkover enabled the future extent of channel change to be predicted. The channel is a highly active and dynamic gravel bed system, having migrated extensively across the river valley approaching the River Eden confluence. The project was commissioned by landowners requesting recommendations to manage the future flood hazard posed by the Swindale Beck due to their concerns over its active and migratory nature. The study identified a number of short to long-term management recommendations, including:

- planting vegetation/trees to create a buffer strip to protect against erosion
- setting back road and electricity pylon to create an increased buffer width
- using available flood plain to create flood storage areas by reconnecting palaeochannels and constructing backwater areas
- creating upstream flood plain attenuation storage (methods such as reconnecting palaeo channels and constructing backwater areas)

The study also identified potential sources of funding, for example, the government’s Countryside Stewardship scheme SW12: ‘Making space for water scheme’, and indicative costs for the identified management solutions.

A detailed historic trend analysis was completed to assess change in channel morphology over time and to determine the influence of historic channel modification and land use change within the catchment. This analysis combined with the assessment of current geomorphological conditions allowed future channel change to be predicted over 3 timescales (short, medium and long term). This highlighted potential future flood risks to infrastructure, which could subsequently be used to inform management recommendations.

Figure A-1 illustrates the digitised channel flow routes of the Swindale Beck study reach during 2017, 2016 and 2015, determined from Google Earth imagery. The Swindale Beck was hit by Storm Desmond in December 2015, and therefore by mapping these 3 consecutive years of channel planform, the morphological impacts of this flood event could be established. By comparing the 2015 and 2016 channel planforms, several areas are shown to have experienced extensive loss of land and channel movement. However, these areas are known to have subsequently been managed with land infilling, bank reprofiling and the placement of new bank protection, causing the channel form to have almost fully returned to its pre-Storm Desmond course in 2017. Despite the recovered channel planform, by mapping the main changes in planform following this peak flood event, the areas most susceptible to future channel change and flood hazard are highlighted.

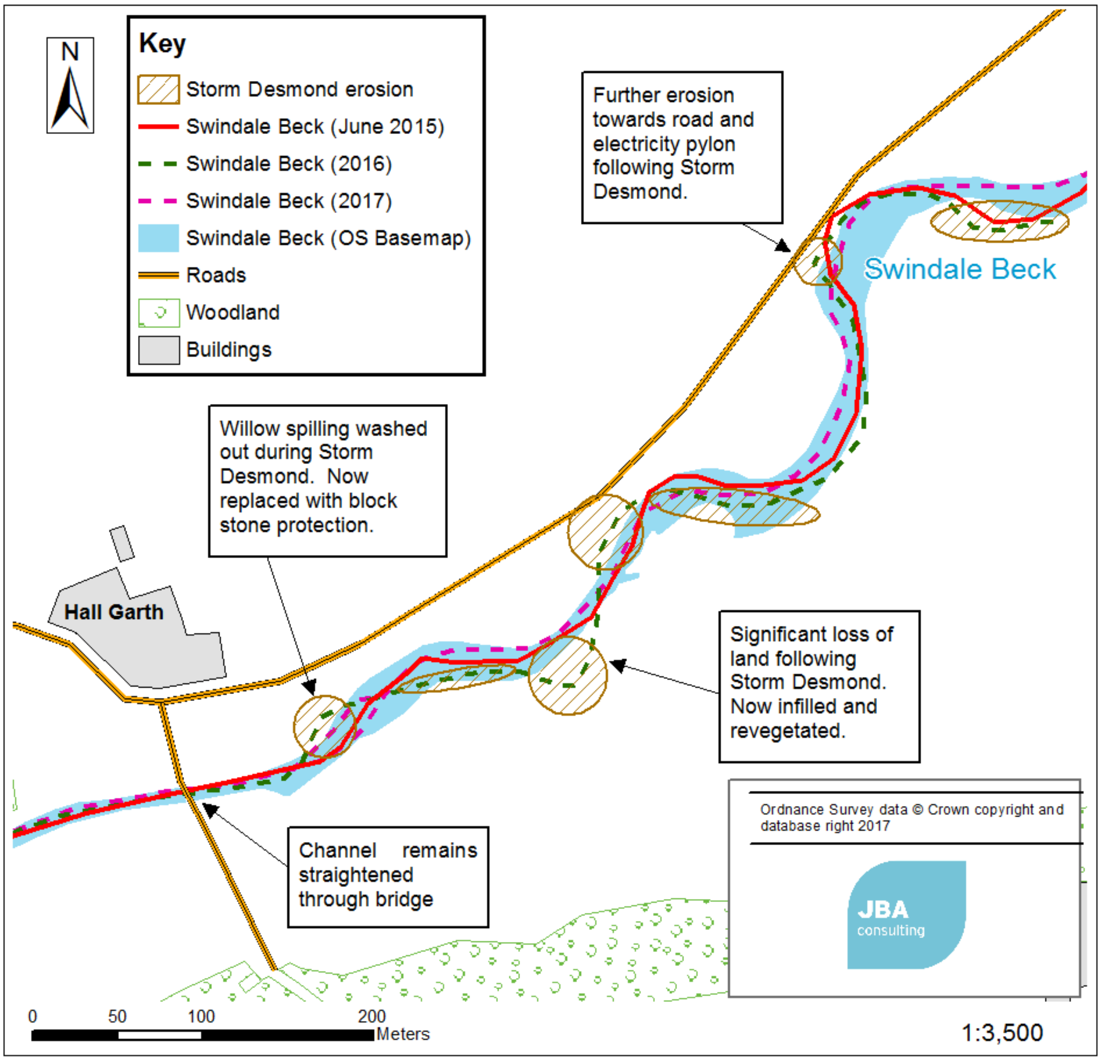

Figure A-1 Swindale Beck planform between 2015 and 2017, illustrating the erosion caused during Storm Desmond

Based on historic and present channel fluvial geomorphological processes observed throughout the study reach, distinct zones of channel activity were classified. Predictions of future channel change were subsequently focused within the 'highly active' zones, separated into 3 timescales; short (1 to 5 years), medium (5 to 20 years) and long-term (>20 years). Figure A-2, Figure A-3 and Figure A-4 illustrate the main channel change predictions over the 3 timescales. The short-term predictions highlight the main areas of infrastructure that are 'at risk' from future bank erosion. For the long-term timescales, it is not possible to accurately predict future channel migration, and therefore a predicted zone of channel migration was developed by analysing the current channel condition, topography and location of paleochannels (observed in LiDAR imagery).

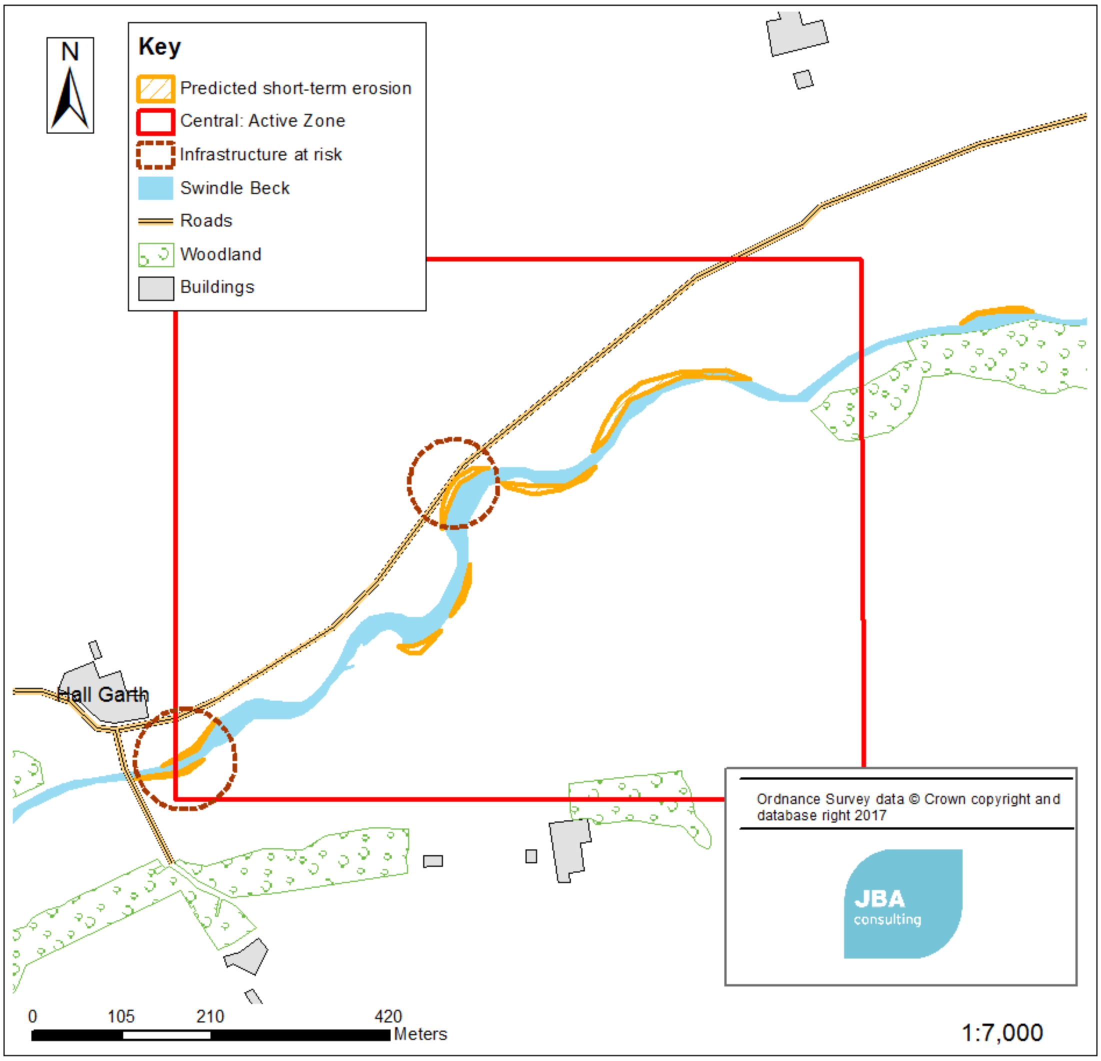

Figure A-2 Swindale Beck short-term channel change predictions

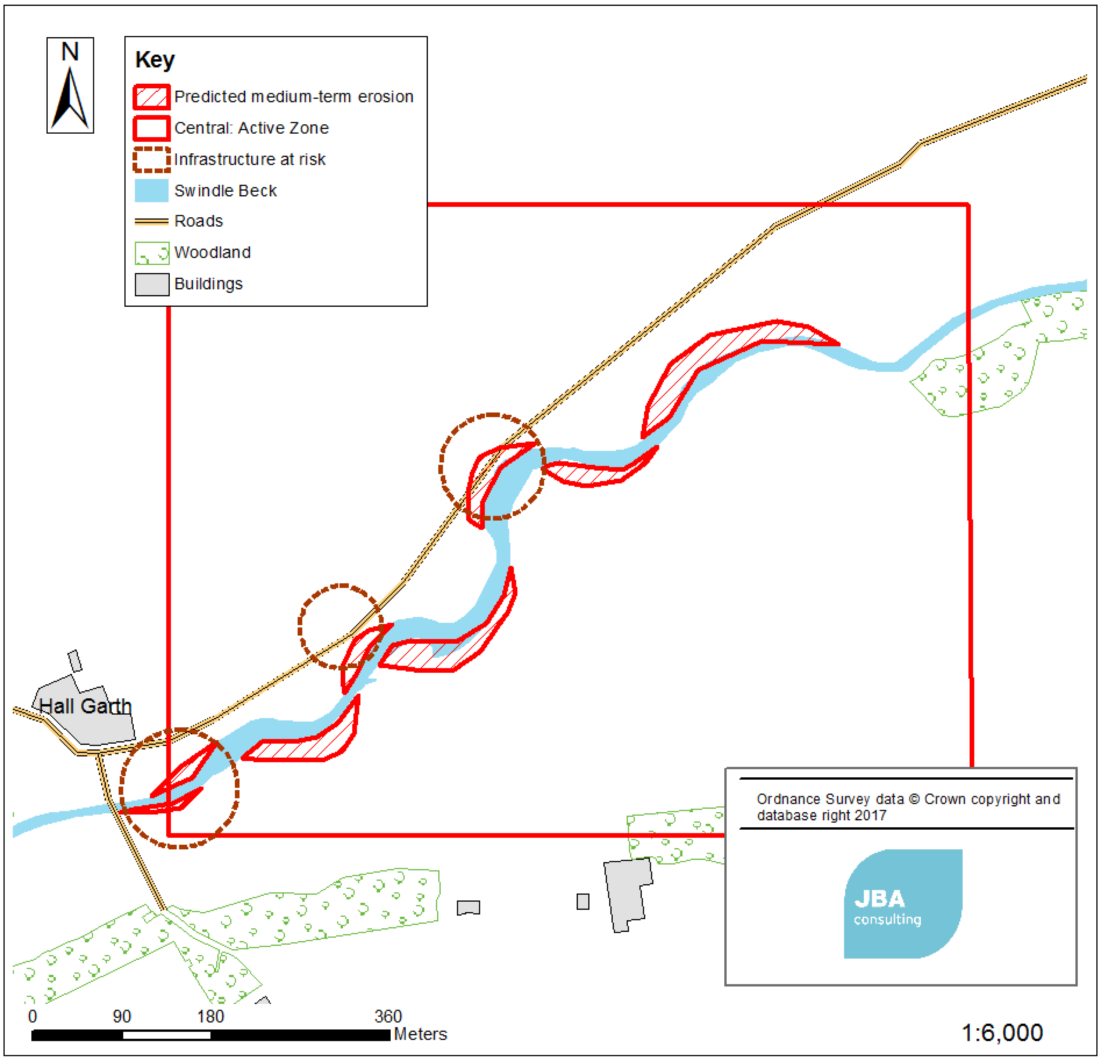

Figure A-3 Swindale Beck medium-term channel change predictions

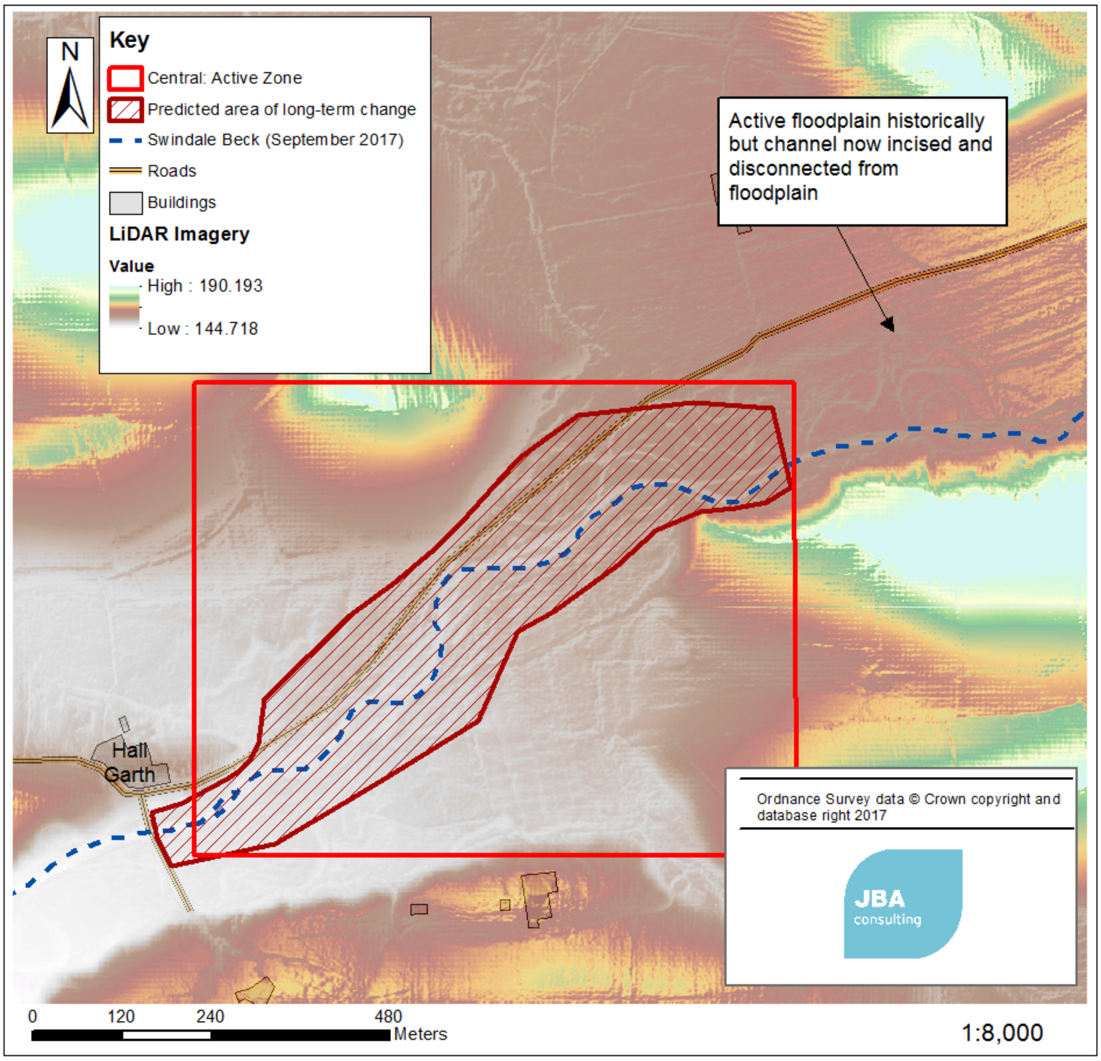

Figure A-4 Swindale Beck long-term channel change predictions

A2 Case study: Coledale Brook

JBA Consulting was commissioned in 2016 by the Environment Agency to carry out an assessment of the flood risk impact of large gravel shoals at several locations across Cumbria. One assessment was carried out on the Coledale Brook at Braithwaite.

The Coledale Beck is a minor tributary of the River Derwent, rising north east of Eel Crag in the Derwent Fells. It flows through Braithwaite before joining Newlands Beck, east of the town. Upstream of Braithwaite the gradient of the river is steep, however, through the town the gradient is shallower and gravel is known to deposit along the bed. In particular, the sections either side of the road bridge near the village shop in the centre of the town are known to accumulate gravel and cobble deposits. The assessment investigated whether gravel accumulation impacts flood risk to the properties in the flood plain.

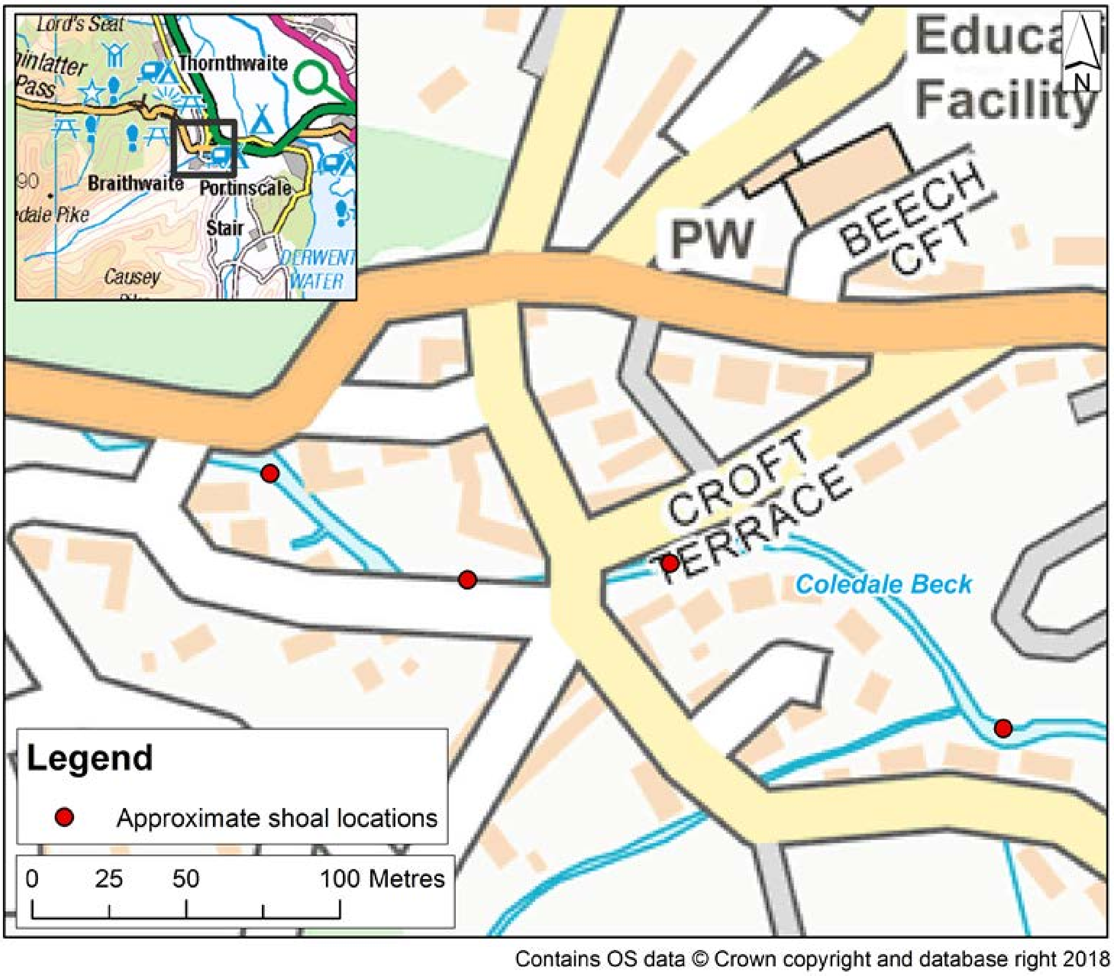

Figure A-5 Shoal locations in Braithwaite

A JBA geomorphologist took photographs during a site visit in July 2017 to better understand the location and distribution of gravel shoals in the area (Figure A-6). According to anecdotal evidence from a local resident, gravel tends to accumulate across the full width of the channel, up to a level in line with the concrete step on the right-hand side (shown in Figure A-6).

Figure A-6 Coledale Beck through the centre of Braithwaite

The Coledale Beck through Braithwaite is represented by the Environment Agency's existing Braithwaite (2016) model. The channel and flood plain in the vicinity of the shoals are represented in a linked 1D-2D format using Flood Modeller-TUFLOW software.

Gravel accumulation in the Coledale Beck at Braithwaite had not been investigated before the assessment and there was no history of regular monitoring. There was therefore no historic survey available to inform the gravel assessment apart from the survey data collected in 2016 to create the hydraulic model. The existing model was considered the most up-to-date representation of the channel and was used to inform baseline conditions.

Artificial cross sections were produced for each shoal location to represent sediment accumulation and the corresponding increase in gravel shoal height. These sections were created from the baseline cross sections; bed levels across the shoal were raised to represent the likely growth in gravel shoal height based on an understanding of the local channel from the survey information and site visit.

The impact of the different gravel shoal heights was investigated using the 20%, 5%, and 1% AEP events, using existing hydrology.

Two gravel scenarios were modelled to test the impact of gravel accumulation (GA) on flood risk. The first scenario (GA1) tested up to a 0.3 m increase in shoal or bed levels, which is the approximate height of the concrete step above the baseline bed levels. Gravel is understood to reach this level following deposition. The second scenario (GA2) tested a more extreme rate of deposition, with up to 0.6 m increase in shoal or bed levels. Example cross sections for 2 locations in Braithwaite illustrating the baseline and gravel accumulation scenarios are shown in Figure A-7 and Figure A-8.

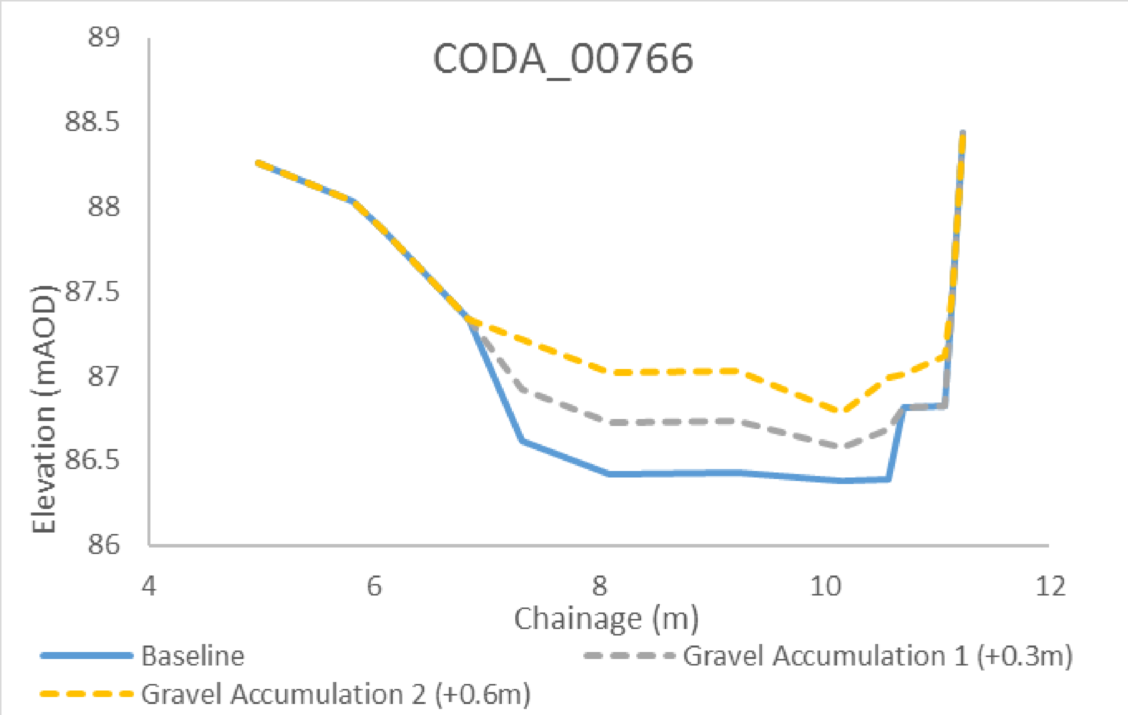

Figure A-7 Example cross sections for baseline and gravel accumulation hydraulic model scenarios

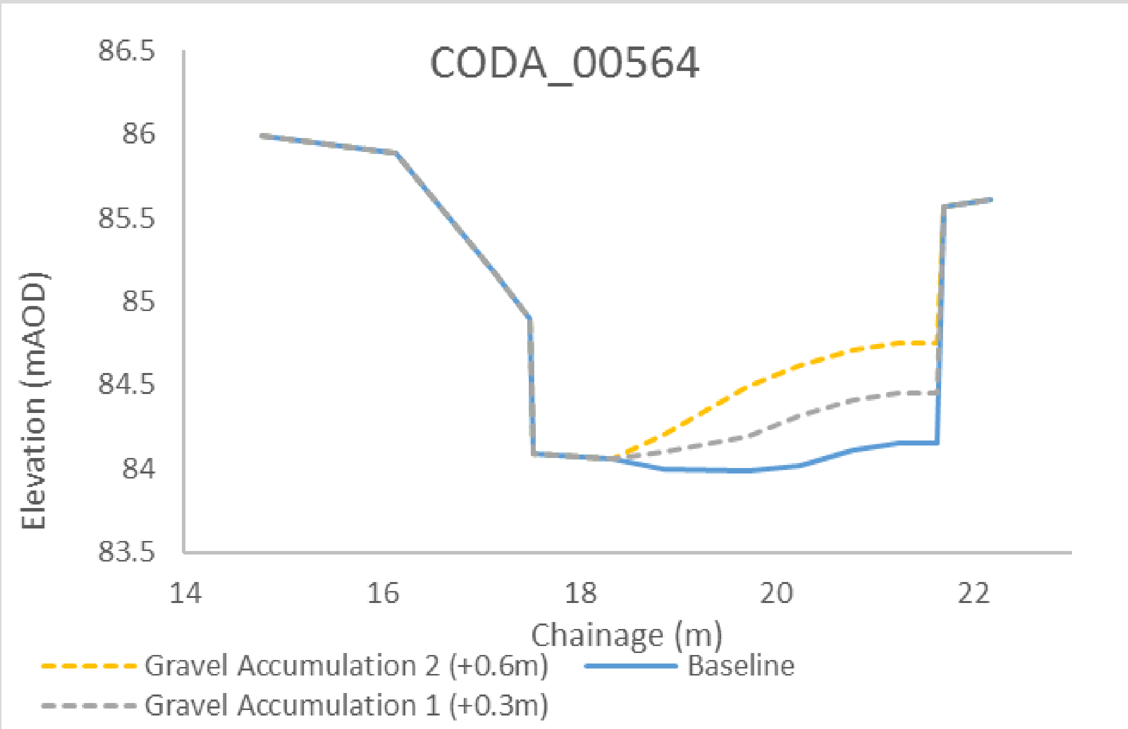

Figure A-8 Example cross sections for baseline and gravel accumulation hydraulic model scenarios

Hydraulic modelling results from the baseline and gravel accumulations scenarios are shown in Figure A-9. There is an increase in flood extent between the baseline results and the gravel accumulation results, with the larger shoal producing the greater flood extent. The increased shoal heights in the channel decreases channel capacity and forces water out-of-bank further upstream than where it originates in baseline conditions. This creates a new flow route to the north-east and south of the beck, resulting in increased flood risk to properties in the centre of Braithwaite.

Figure A-9 Flood outlines for the 20% AEP event

The number of buildings, as indicated by polygons shown on Open Source local mapping, impacted by the flood outline increased from approximately 17 in baseline conditions to 45 and 53 in GA scenarios 1 and 2, respectively. These figures do not represent an accurate number of properties, as it was unknown which building polygons shown on OS mapping are properties and how many properties may be within the outline of each building footprint (the National Receptor Dataset data was not available for the study). However, they provided an indication of the change in flood risk associated with the modelled shoals. Flood depths in the new flow route in the GA2 scenario, which tests up to a 0.6 m increase in shoal height, reached 0.6 m (Figure A-10).

Figure A-10 Difference in depths between baseline and GA2 (20% AEP)

The results showed increased flood risk to properties in both gravel accumulation scenarios, indicating that the capacity of the channel is sensitive to changes in bed level and shoal heights.

This was not surprising, given the size of the channel and the relative loss of capacity the change in cross-sectional area causes. The sensitivity was most pronounced in the lower return periods, whereas in the 1% AEP event the effects of the shoal were more drowned out.

Given that the 0.3 m increase in bed level and shoal height is shown to increase flood risk to property significantly, it was recommended using this scenario to set the flood risk threshold within Braithwaite. Identifying a trigger level for the shoal will allow the gravel to be removed before the threshold is met. The trigger level depends on the identified threshold as well as the average amount of deposition that happens during a flood event.

Since monitoring has not been carried out through Braithwaite, there was no historic survey available to compare how shoal profiles might have altered during or following a large flood event. It was therefore not possible to estimate the average amount of deposition that may occur during a given high flow event, which, if available, would be useful to determine how much below the determined threshold level a trigger level should be set. In the absence of this information, the trigger level was set 0.1 m below the threshold. This could be revised if this data becomes available in the future.

Four trigger level locations for monitoring were chosen through Braithwaite. They were selected as they were considered to be the primary locations for gravel accretions. Each trigger level was plotted up against the baseline cross section and the flood risk threshold (defined by the first gravel accumulation scenario tested in this study). An example is shown in Figure A-11. The shape of the channel is likely to change as the shoal grows and shrinks and as gravel is deposited at various points along the channel. The trigger location provides a reference point to monitor changes in the shoal height, but it should be noted that gravels will not necessarily be deposited along the shoal in line with the profiles shown in the figure.

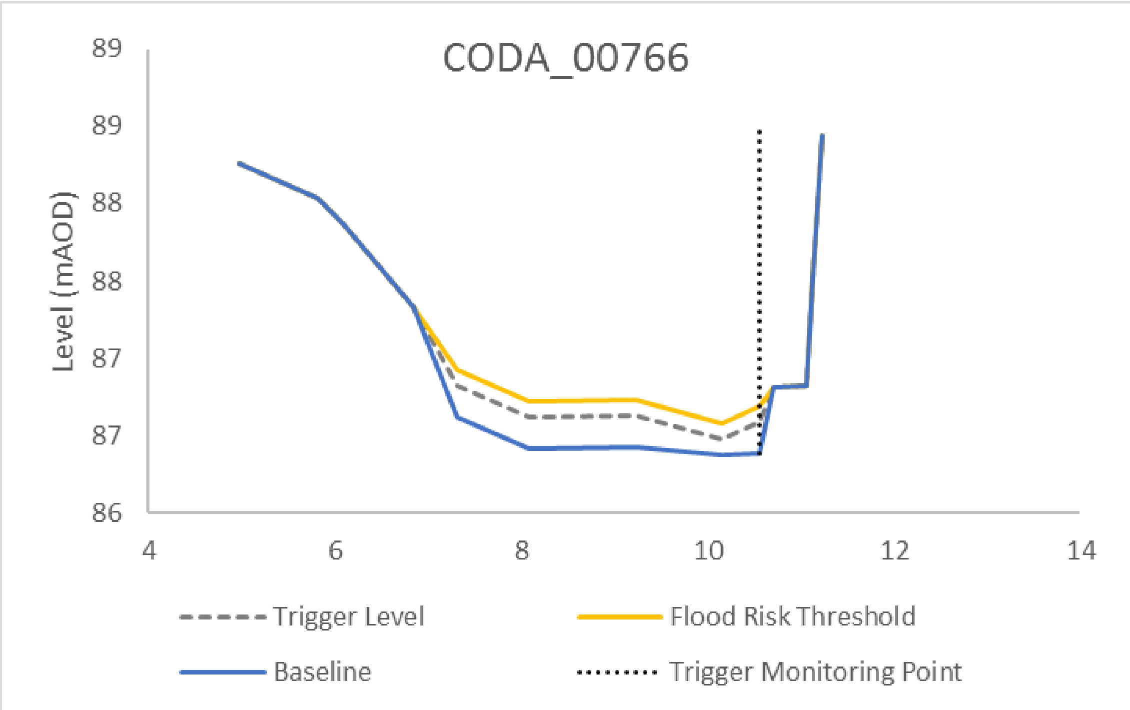

Figure A-11 Example trigger level

The thresholds and trigger levels were derived using available data. A number of assumptions were made to carry out the assessment, including the length and height of the shoals following accumulation. Should any further data become available, such as on the movement of gravel in these locations and the average deposition of material following a large flood event, these threshold and trigger levels should be reviewed and updated where necessary.

Monitoring of the channel through Braithwaite was strongly recommended, in particular at the locations chosen to set the flood risk thresholds.

In future situations like this, having national data on potential channel change and geomorphological activity (as explored in Report 1 and this report) would provide the initial analysis and help target further investigation. For example, knowing whether there is a tendency or potential for either deposition or erosion would help indicate whether shoals are likely to be mobile (entrained) during floods. This information would support decision making in the absence of monitoring, and help to identify the locations where investment in monitoring programmes should be targeted.

A3 Case study: River Irwell

In February 2016, JBA Consulting was commissioned by Electricity North West to carry out a geomorphological assessment of an electricity pylon near Bury, which was being undermined by the River Irwell following the severe flood events of December 2015. The floods generated substantial erosion of the left bank of the river, on which the pylon is situated, causing serious concerns over its stability and safety.

The purpose of the study was to assess the past and current geomorphology conditions of the River Irwell in the vicinity of the pylon to understand the processes that led to the erosion of the bank, the future erosion risk, and to investigate potential, low risk sites suitable for relocating the pylon. The study considered the effect of the existing weir immediately downstream of the pylon site, and what the likely long-term situation would be if the weir collapsed or failed. In addition, the study provided recommendations on measures to protect apparatus from current and future erosional risk. This included protecting the pylon in its current location using piling or rock armour/stone block bank protection, as well as erosion protecting the flood plain surface behind the piles/rock and beneath the pylon from erosion or relocating the pylon to a low risk zone.

Analysis of aerial imagery and historical maps showed that the channel position has shifted over the last century (in particular the last 50 years), gradually pushing against the left bank and shifting the channel towards the east. An outline of the historic channel is shown along recent aerial imagery in Figure A-12. Historic maps show the channel around the start of the nineteenth century as being more in line with the smaller channel, right of the island upstream of the weir. Additionally, downstream of the weir the channel is shown to be far wider, as the deposition present today did not exist around this time, possibly due to historic sediment removal regimes. Sediments began depositing upstream of Hinds Mill/Waterside Mill weir between the 1940s and the 1960s to form the significant mid-channel island that exists in the current conditions. It was evident from the old maps that the right-hand channel (looking downstream) used to be the dominant channel. However, over time this has switched (possibly due to the operation of the mill stopping), resulting in the watercourse eroding and carving out the left-hand bank and causing the channel to split. The deposition at the upstream extent of the right-hand channel, evident in Figure A-12, supported this theory.

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Figure A-12 Change in channel position over last century

The pylon on the left bank was under severe threat as a result of active fluvial undercutting and erosion of the bank. One of the 4 steel legs was exposed in the channel and a second was also at risk of becoming disconnected from the bank (Figure A-13). This was a result of the severe December 2015 floods during which there had been significant erosional pressure on the left bank and flood plain. It is understood that the channel had been relatively stable before this event, excluding the long-term trend indicated by the historic maps. Approximately 100 m^2 of land was estimated to have been eroded from the bank underneath the pylon in the 2015 floods.

While the pylon is situated on the inside bend of the river before the weir, locally it is positioned in an area that is subject to erosion from the main flow route of the left-hand channel. It would also appear that the meander upstream of the weir is migrating downstream. Although unverified on site due to access and visibility, it is possible that hard bank protection on the right bank is restricting movement of the channel, causing higher velocities in the immediate reach of the river. This would cause greater potential for erosion on the left bank than would be expected otherwise. The position of the portion of land where the pylon is sited means that in-channel velocities are greater at this point, which further places the area at a higher risk of erosion.

Figure A-13 Position of pylon following erosion

The exposed banks are composed of a top layer of soil with a mixture of sand and clay material beneath. It appeared to be mostly unconsolidated and easily erodible. The way the bank had been eroded, with an indent around the pylon but with the main inside channel bend seemingly largely unaffected, suggested that during the 2015 flood event circular, eddy turbulence was responsible for much of the erosional action. According to the Hjulström curve, the unconsolidated sediment on the left bank would be particularly vulnerable to erosion within the typical velocities that range in the channel in the baseline hydraulic model (Figure A-14). The curve shows that at higher velocities generated during large flow events, the erosional potential would increase further still.

The analysis showed that there is a risk of continued erosion of the land on which the pylon is currently located. The historic maps show a trend in which the channel is gradually shifting eastward. The modelling results place the channel velocities in the erosive category according to the Hjulström curve; the velocities are likely to be slightly higher on the left bank where the pylon is situated due to the channel shifting eastward and causing the flow route to carve into the left bank. These factors place the land adjacent to Hinds Mill/Waterside Mill weir at risk.

Modelling results showed that if the weir failed, the water level upstream would lower as the channel becomes less impounded. This would lower water levels in the vicinity of the weir and increase the potential for lateral erosion as more of the bank becomes exposed. Velocities are shown to increase marginally with the failure of the weir, as more water is drawn down the channel. The likely impact of the weir failing is a period of incision as the channel bed adjusts to the new water level, which will be followed by stability in terms of the bed level. However, the exposed banks could be subject to further instability.

Relocating the pylon away from the channel would reduce the risk, but, as the analysis shows, there would still be a high residual risk of bank erosion. Bank protection measures could lower the residual risk.

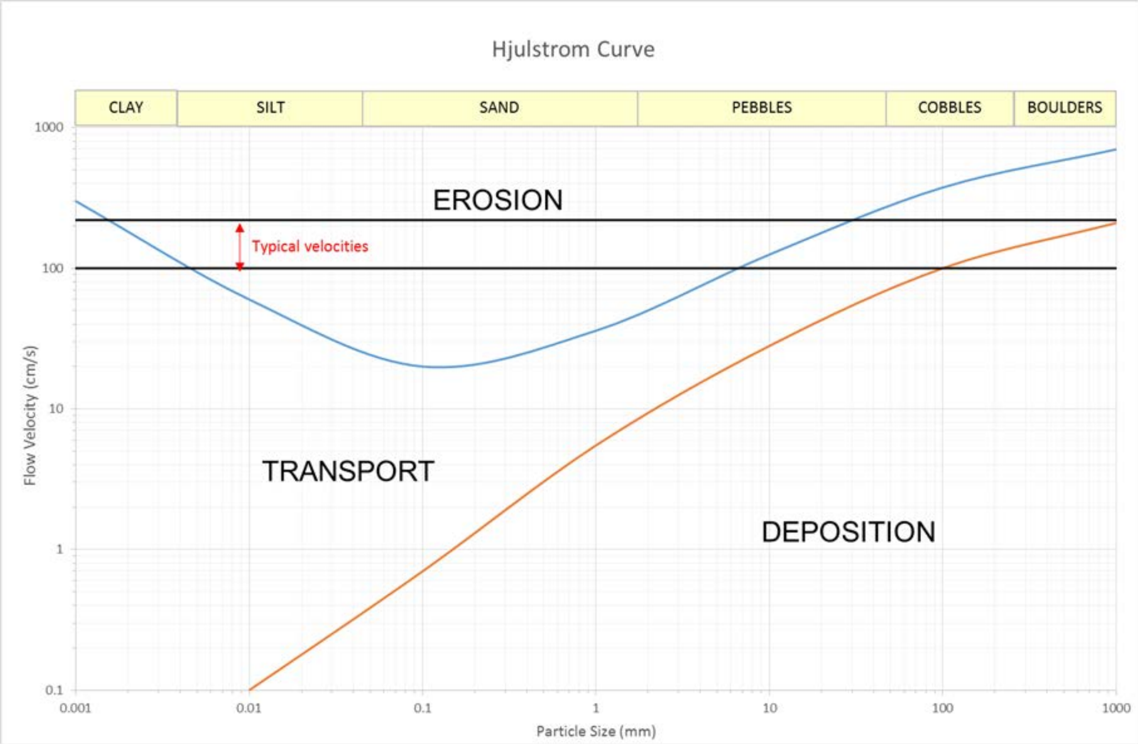


Figure A-14 Hjulström curve and typical velocities in a low order flood event

A4 Case study: River Great Ouse

JBA Consulting was commissioned to carry out a breach analysis along the River Great Ouse defences at Ely, Cambridgeshire in order to provide information on the nature of flood risk at a proposed development site.

The Environment Agency's Flood Map for Planning shows that the site is situated in flood zone 2 and flood zone 3 (River Great Ouse's 1,000-year and 100-year flood plain) and is protected by an embankment running adjacent to the eastern site boundary. Hydraulic modelling was used to assess the impact of a breach of these defences at the site. The study provided information on the nature of flood risk at the site due to a breach of the defences and followed government guidance with regards to development and flood risk.

An existing model was reused and updated for the modelling study. In order to represent a breach of the River Great Ouse defences in relation to the site, 3 breach locations were modelled as shown in Figure A-15.

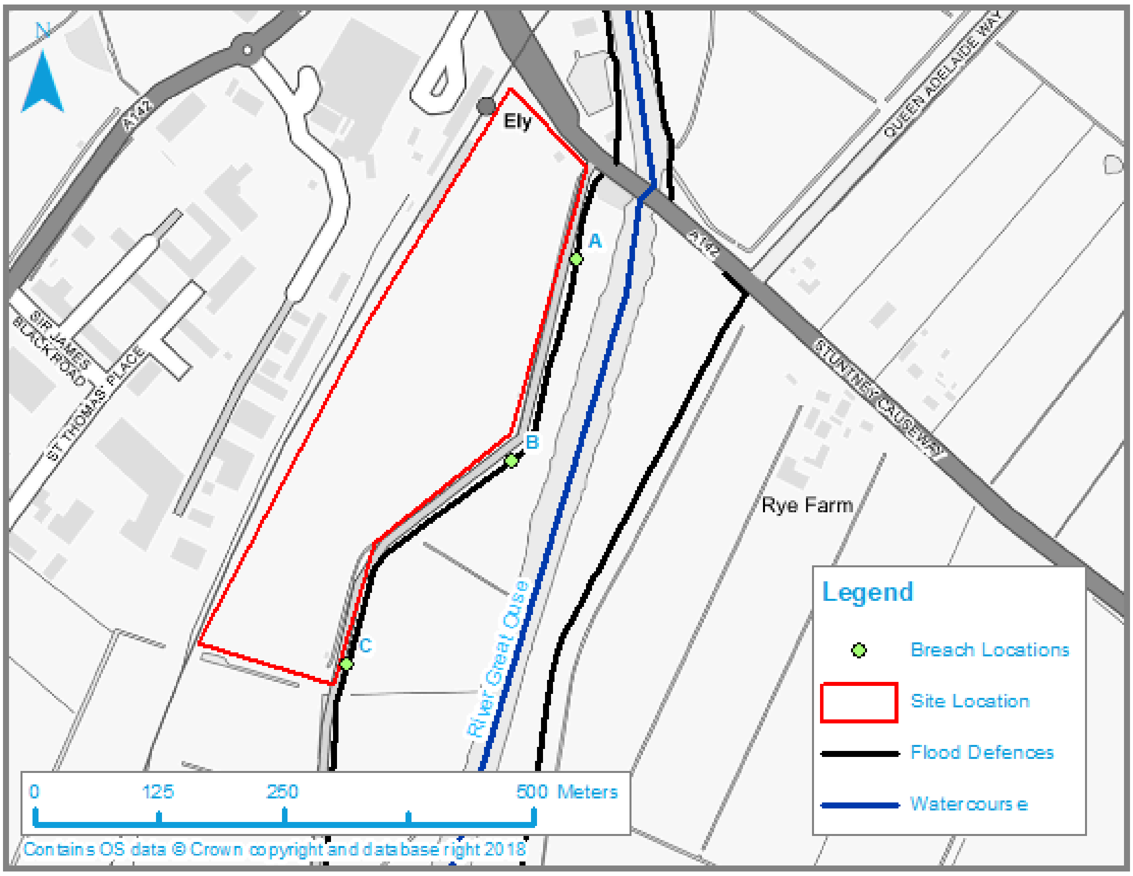


Figure A-15 Breach locations

The breach parameters were based on the Environment Agency's 'Breach of Defences Guidance - Modelling and Forecasting Technical Guidance Note V1' dated 14/09/2017.

In the Flood Modeller-TUFLOW model, a 50 m wide breach in the earth embankment was simulated in the 3 breach locations. For modelling purposes, it was assumed that a breach would take one hour to be generated from just before the peak flow is reached in the river channel at the nearest 1D Flood Modeller node. This means that the breach was fully implemented in the model at the time the peak flow in the channel occurred.

From the model results, flood extents, depths, levels and hazard to people classification grids were generated. Flood extents and flood depth comparisons are shown in Figure A-16 and Figure A-17. The breach analysis shows that a breach of the River Great Ouse defences adjacent to the site during a 100-year plus 35% climate change event would result in much larger flood extents and greater flood depths compared to the baseline scenario.

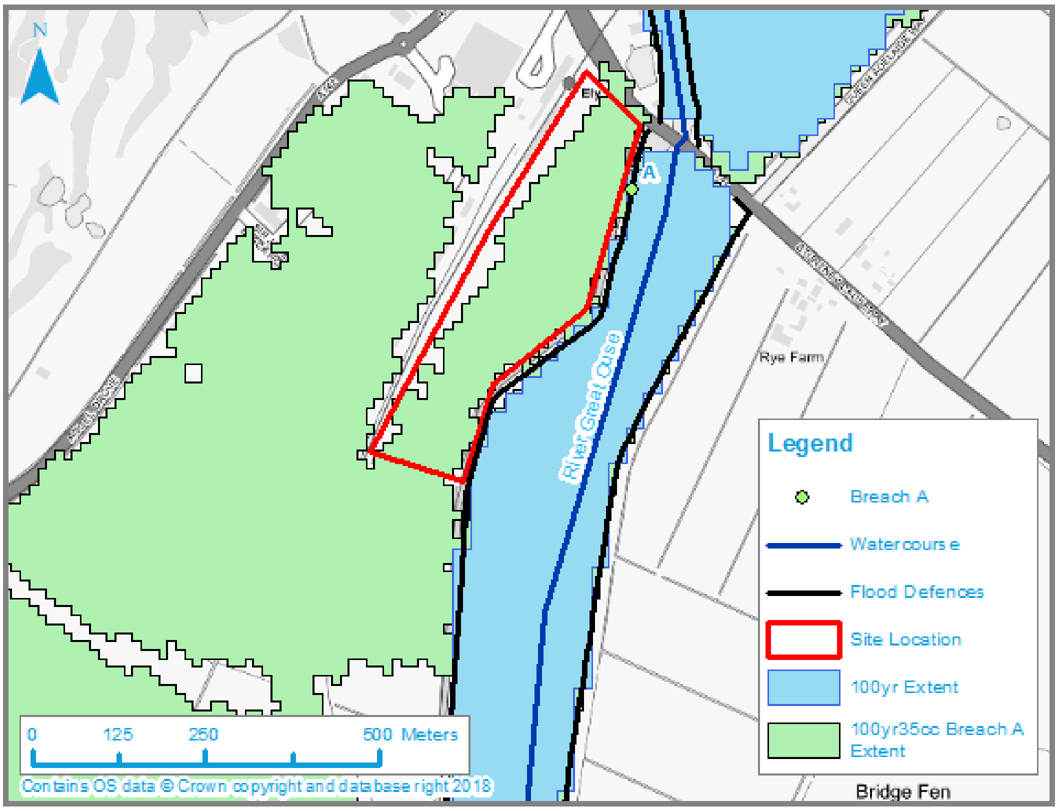


Figure A-16 Baseline 100-year plus 35% climate change Breach A flood extent

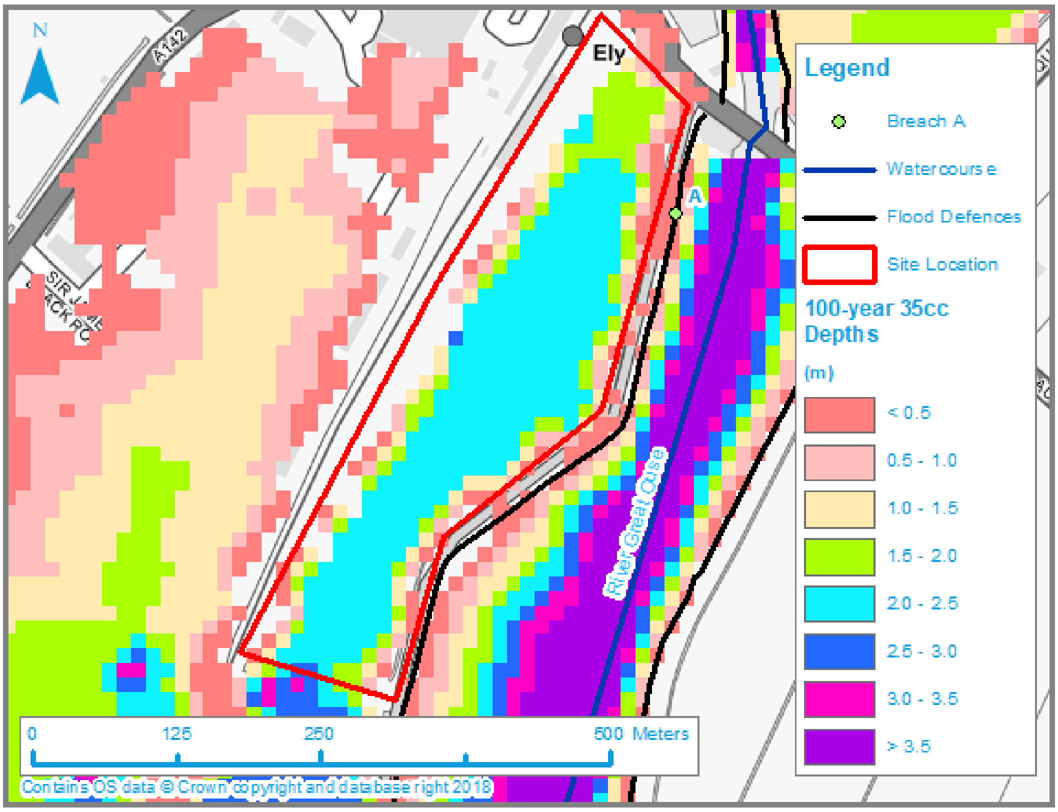


Figure A-17 Flood depths during the 100-year plus 35% climate change Breach A scenario

Appendix B: Multi-criteria analysis

Following the trial phase, it was deemed necessary to revisit the multi-criteria analysis (MCA) quality scoring based on the information and knowledge gained when applying the method to the test catchments. The results of the MCA scoring are presented below. The reasons for the scores are also given. Although the shear stress data mining method was not formally included in the method trials, a parallel study was carried out that gave greater insight into the method. Consequently, the shear stress data mining method has also been included within the MCA so it can be compared with the other 3 shortlisted methods: ST:REAM, CAESAR-Lisflood and half-yield method.

Of the 4 methods, CAESAR-Lisflood was ranked the highest in terms of the quality criteria, with a final moderated score of 78. The shear stress data mining method was ranked second, with a final moderated score of 71. ST:REAM and the half-yield method were ranked third and fourth, with scores of 61 and 52, respectively.

Table B.1 MCA quality scores following the trial phase

Quality criteria (weight)	**ST:REAM**		**CAESAR-Lisflood**		**Half-yield**		**Shear stress data mining**	
	Moderated score		**Moderated score**		**Moderated score**		**Moderated score**	
	Score out of 10	**Weight. score**	**Score out of 10**	**Weight. score**	**Score out of 10**	**Weight. score**	**Score out of 10**	**Weight. score**
How accepted is the method? (10)	10	10	10	10	1	1	5	5
	Accepted method that has been run nationally in Scotland. SEPA uses the results for desk assessment for regulation or restoration, as well as within national flood risk assessments.		Published and accepted method. Used in over 60 peer-reviewed studies internationally.		Unpublished, recently developed method, although based on sound scientific theory.		Science underpinned by published research/methods. Data-driven modelling is now well established as a valid method.	
Level of input data required (10)	10	10	5	5	10	10	10	10
	Largely requires readily available data sets, including IHM DTM, OS MasterMap, CEH grids, DRN		Some complex data sets required such as hourly rainfall, grain size data and flow gauging for model calibration. However, the level of complexity is user-defined.		Uses readily available RHS and DRN data, although the method relies heavily on the accuracy of this data set. Model can be applied where data is available (missing data is not critical).		Uses readily available data sets, needs little data.	
Complexity of method (5)	5	2.5	5	2.5	5	2.5	10	5
	Relatively low level of complexity, although trials identified some potential difficulties with the GIS applications.		Not overly complex as a basic model, however, increasing levels of complexity can be added (for example, in-channel structures		User-interface is relatively simple, with a fairly complex scientific theory coded in the background.		Low level of complexity.	

Quality criteria (weight)	ST:REAM		CAESAR-Lisflood		Half-yield		Shear stress data mining	
	Moderated score		Moderated score		Moderated score		Moderated score	
	Score out of 10	Weight. score	Score out of 10	Weight. score	Score out of 10	Weight. score	Score out of 10	Weight. score
			and grain size distribution data).					
Ability to provide geomorpho-logy baseline (10)	5	5	10	10	5	5	5	5
	Good ability at providing a catchment-scale understanding of certain processes. Stream power balance for QMED might not be appropriate for all river types. Results validation illustrated wide variation in performance across catchments in terms of predicting geomorphic processes (18% to 60% success rate across the 3 catchments).		Good ability since it includes geomorphic detail, as well as sediment balances. Results validation illustrated 50% success rate against fluvial audit data in the Kent catchment. Lacked accuracy mainly in areas of channel modification.		Good ability where RHS data is available, although highly dependent on accuracy of this data set. No modelling of lateral activity. Data are generated for individual cross sections, but the approach does not simulate spatial linkages in sediment movement between reaches. Validation of results illustrated the most consistency in terms of predicting geomorphic processes (38% to 50% success rate across the 3 catchments), however largely dependent on RHS data availability.		Results validation showed good correlation with fluvial audit data at a fine resolution. Results also make sense when combined with wider catchment data to understand valley-scale processes. Accuracy shown to reduce in areas of tree cover.	
Ability to include climate change (10)	1	1	10	10	10	10	5	5
	The method cannot account for extreme flows and as ST:REAM outputs stream power imbalances between reaches in the form of quotients, any percentage increase to QMED would cancel out.		The effects of climate change can be incorporated into CAESAR-Lisflood by adjusting rainfall inputs according to climate change projections using the UKCP09 weather generator, as demonstrated by Coulthard and others (2012).		The flow duration curve is intrinsic to the method (incorporating the impact of the high magnitude, low frequency events) and there is scope for adjusting the flow regime to account for climate change by manipulating the flow duration curves using the outputs of the Centre for Ecology and Hydrology's Future Flows project.		Lacks full ability to account for CC, however an estimate of the sensitivity of the spatial distribution of erosion and deposition potential to increased rainfall could be gained by comparing the 1% and 0.1% AEP.	
	5	7.5	5	7.5	5	7.5	10	15

Quality criteria (weight)	ST:REAM		CAESAR-Lisflood		Half-yield		Shear stress data mining	
	Moderated score		Moderated score		Moderated score		Moderated score	
	Score out of 10	Weight. score	Score out of 10	Weight. score	Score out of 10	Weight. score	Score out of 10	Weight. score
Ability to create national coverage data (15)	Feasible, but testing has shown that there would be some hard work involved, including creating the correct topology/ relationship of the river branches in all catchments in the UK. Analysis and quality assurance would be needed at catchment scale, increasing time requirements.		Resource (including computer power and skilled staff) and time intensive. Would require individual basin models to be developed for each catchment. Ideally each calibrated to a downstream gauge to increase confidence in outputs. Level of detail incorporated in model parameterisation can be user-defined, which would alter the time and resource requirements.		Currently coded requiring 4 input files per catchment allowing national scale implementation in a batch processing format as there are no shared files for each catchment. A virtual (unused) machine would be required as the script accesses Excel during operation, meaning potential disruption to user. Since the model would be applied 'where RHS data is available', this could potentially result in incomplete coverage.		Already implemented at a national scale (for a single grain size and 3 return periods). Runs took 12 hours each to complete, therefore, national scale data is achievable in a short time frame. Potential limitations need to be addressed (such as reduced accuracy in lower catchment reaches), and further improvements are required to refine method outputs (such as majority filtering and removing woodland).	
Consistency in application (5)	10	5	5	2.5	5	2.5	5	2.5
	On the surface appears to be consistent, however the method trials revealed potential inconsistencies related to the need for manual checks on automated processes. Specifically related to the regression relationship with the DA CEH grid - this needs reviewing to check the regression relationship due to inaccuracy over 400 cumecs. Results validation showed that		The consistency depends on the data available for each catchment. For example, coverage and resolution of DTM and rainfall gauges.		Consistency highly reliant on coverage and accuracy of RHS survey points. Results validation showed that the half-yield method was the most consistent method across the 3 catchments.		Method is consistent in terms of application, however the accuracy may be greater in the headwaters.	
Expertise required to apply method (5)	5	2.5	5	2.5	5	2.5	10	5
	User with GIS expertise is required, especially		Application is relatively complicated for		Catchment delineation for FDC creation		Relatively low level of expertise required, however	

Quality criteria (weight)	ST:REAM		CAESAR-Lisflood		Half-yield		Shear stress data mining	
	Moderated score		Moderated score		Moderated score		Moderated score	
	Score out of 10	Weight. score	Score out of 10	Weight. score	Score out of 10	Weight. score	Score out of 10	Weight. score
	knowledge and experience of working with spatial data and relational tables. Checks are required on some of the GIS processes, for example correct aggregation of points, accurate delineation of reach boundaries and most appropriate R value for the zonation algorithm.		someone with no modelling experience, but this could be overcome through specific user-training courses, senior oversight and quality assurance		would need competent GIS skills. Application of method is simple with coded spreadsheets, assuming reasonable Excel skills.		some geomorphology knowledge is required to set the correct depositional threshold for different catchments (to reflect the different processes operating, such as bed armouring).	
Quality of outputs (10)	5	5	10	10	5	5	5	5
	Method does not deal with the complexities of predicting sediment load imbalance, the expenditure of energy in lateral erosion or lateral inputs of sediment. However, testing by SEPA showed that the model results were precise enough to show local changes, for example, at a scale of around 100 m.		Detailed reach scale mapping of erosion and depositional processes over time. The only method to incorporate lateral inputs of sediment from slope processes.		Potential to provide locally detailed data based on at-a-site efficiency, although accuracy of results is dependent on reliability and availability of RHS data points.		The outputs are visually simple yet detailed locally (2 m resolution). Some inaccuracies identified, particularly in areas of woodland which would require further method research and development.	
Use as a manageme-nt planning tool (5)	10	5	10	5	5	2.5	10	5
	Given the spatial coverage (nationwide) and the resolution (local), the model would be very helpful. Demonstrated to be a useful national tool by SEPA who use it for desk assessment for regulation/ restoration as well as strategic		Potentially very useful due to the detailed level of outputs, although dependent on resources available for interpreting the results. Current limitations in areas of channel realignment, although equally this could be used to highlight potential		In areas with available data the tool could be potentially useful by highlighting key geomorphological processes and probable method of channel adjustment. Although lack of data is a key limitation for using as a management planning tool at the national scale.		Potentially very useful due to detailed level of outputs, although dependent on further investigation into interpreting results, such as majority filtering and a decision support framework.	

Quality criteria (weight)	ST:REAM		CAESAR-Lisflood		Half-yield		Shear stress data mining	
	Moderated score		Moderated score		Moderated score		Moderated score	
	Score out of 10	Weight. score	Score out of 10	Weight. score	Score out of 10	Weight. score	Score out of 10	Weight. score
	support for flood risk maps.		restoration opportunities.					
Ability to identify benefits for asset managers (10)	5	5	10	10	1	1	5	5
	Method does not permit accounting for net erosion or deposition rate which is what asset managers need. Lateral instability is also not accounted for. However, its strength lies in highlighting fundamental network behaviours (for example, eroding reaches) that can feed into asset management planning.		Incorporates sediment inputs from valley slopes and also includes modelling of lateral erosion processes. Gives rates of accumulation and net erosion/deposition, including lateral erosion. Potential to illustrate geomorphological change such as landform evolution and channel avulsion.		Method does not permit accounting for net erosion or deposition rate which is what asset managers need. Lateral instability is also not accounted for. Can give detail of key processes at point locations, however dependent on data availability.		Method does not permit accounting for net erosion or deposition rate which is what asset managers need. Could indicate potential areas for channel migration. Can give detail on key processes (for example, potential for erosion and deposition), but dependent on further investigation and interpreting results.	
Interpreta-tion needed (5)	5	2.5	5	2.5	5	2.5	5	2.5
	The outputs are visually very easy to interpret. However, it is less easy to understand exactly what they mean. Some geomorphological understanding is needed to know if the spreadsheet is producing sensible results. Threshold for erosion, balance and deposition reaches need to be established, which requires calibration to the current catchment.		Fairly easy to interpret following basic training (once model has been calibrated and undergone quality assurance). Geomorphological understanding required to fully interpret results.		Without geomorphological expertise, there is potential danger of misinterpretation. Initial visual assessment of GIS outputs needs to be supplemented with review of performance factor and effectiveness index to determine dominant geomorphological processes.		Production of GIS layer requires limited interpretation to display key geomorphological processes, although some limitations identified in methods testing show the need for further investigation into the display of model outputs (for example, majority filtering and removing woodland).	
Total		**61**		**78**		**52**		**71**

Appendix C: Method workflows

The workflows are presented in the following sections:

Appendix C1: ST:REAM, including a workflow example of how to incorporate local influencing factors

Appendix C2: CAESAR-Lisflood

Appendix C3: Half-yield

Appendix C4: Shear stress data mining

Appendix C5: CAESAR-Lisflood normalisation

Appendix C1: Method workflow: ST:REAM

C1.1 Overview

ST:REAM is an established method based on published research. Chris Parker (UWE Bristol) ran the model for the Kent catchment and provided guidance and assistance to JBA in running the model for the Stour and the Wharfe catchment. The following section outlines the steps involved in applying the method to the trial catchments.

C1.2 Methodology

1. Set up ArcGIS project

- Create working folder with catchment name as label.
- Create new .mxd file with catchment name as label in working folder.
- Change .mxd file Data Frame co-ordinate system to British National Grid.
- Change .mxd file properties so that relative pathnames are stored.
- Create a new file geodatabase with catchment name as label in working folder.
- Set the new File Geodatabase as the default geodatabase in the map document.

2. Download input data

- (If not already done so) Download the GB national grid squares shapefiles from Digimap.
- (If not already done so) Download the OSOpenRiver shapefile for the UK.
- (If not already done so) Download the CEH Q2 grid for the UK.
- (If not already done so) Download the CEH DA grid for the UK.
- If appropriate (that is, it covers the full catchment) download the catchment boundary shapefile from CEH.
- Use the river shapefile and the 10 km national grid squares shapefile to identify the 10 km grid squares that cover the catchment.
- Download the OS Open Map Local Raster backdrop mapping layer as TIFF files for the required 10 km grid squares – this can be done for 50 10 km tiles at a time.
- Download the OS Mastermap topography layer for the required 10 km grid squares with Format set to File Geodatabase and Layers set to just Water – this can only be done for one 10 km tiles at a time.
- Download the integrated height model 2 m resolution digital terrain model (Environment Agency, Licensed data). Note the most up-to-date and accurate DTM available for the catchment should be used.

3. Import the data into the file geodatabase

- If downloaded, import the catchment boundary shapefile into the geodatabase and save as ‘NRFA_Watershed’.
- Import the ‘TopographicArea’ MasterMap feature classes from the geodatabases representing each of the downloaded tiles into the File Geodatabase.

- Use the ‘Merge’ tool to combine the TopographicArea feature classes into a single feature class labelled ‘OSMasterMap_WaterArea_Unclipped’.
- Use the ‘Mosaic to new raster’ tool to mosaic the LiDAR DTM tiles together. Set the spatial reference to British National Grid, the pixel type to 32 bit floating point, the number of bands to 1, and the cell size to 2 m). Save as LidarDTM_2m.
- Use the ‘Mosaic to new raster’ tool to mosaic the OS Terrain 5 DTM tiles together. Set the spatial reference to British National Grid, the pixel type to 32 bit floating point, the number of bands to 1, and the cell size to 5 m). Save as OSTerrainDTM_5m.
- Use the ‘Mosaic to new raster’ tool to mosaic the OS Open Map Local Raster tiles together. Set the spatial reference to British National Grid, the pixel type to 8 bit, the number of bands to 1, and the cell size to 1 m). Save as OSLocalRaster.
- Check all of the merged layers are correct and then delete all of the, now redundant, original tiles from your geodatabase.

4. Edit the OSOpenRivers feature class to contain a single thread representation of just the study catchment network

- Select all of the channels in the catchment network (Select by location based on intersection with Watershed polygon).
- Export selected channels as new feature class and save in geodatabase (as OSOpenRivers) for study catchment.
- Edit the created feature class to remove any channels not in the network, any secondary channels, or any branches <1 km (Change symbology so that all segments under 1,000 are red and then move round catchment deleting any branches <1 km).

5. Convert the IHM DTM into 2 m contours

- Use the ‘Aggregate’ tool to convert the 2 m LiDAR DTM to a 10 m DTM (cell factor of 5), with the MINIMUM value being used for each cell. Save as LIDARandTERRAINDTM_10m.
- Use the ‘Contour’ tool to convert the aggregated DTM to contours with 2 m spacing. Save as ‘Contours_2m’.

6. (If necessary as no suitable NRFA watershed polygon available) manually draw a watershed polygon feature class, making sure that it crosses the channel at the desired outlet point.

7. Use ‘Catchment Model Builder’ to:

- Clip input data sets (and limit output data sets to extent of watershed).
- Interpolate a DTM from the contour and known river lines.
- Burn a channel network into the DTM using the known river lines.
- Use the ‘Fill’, ‘Flow direction’, ‘Flow accumulation’, ‘Raster calculator’, ‘Reclassify, and ‘Stream to feature’ tools to create a representation of the catchment drainage network.
- Calculate width of MasterMap channel polygons.
- Create points along the channel network where it crosses a contour (for calculating slope).

8. Create a Q2 raster grid

- Crop the CEH DA and Q2 grids to the extent of your catchment.
- Create a random sample of points using the ‘Create Random Points’ tool (constrain to the ‘Channels’ with 10 points per feature).

- Extract the CEH DA and Q2 values to the random sample using the 'Multi values to points' tool.
- Export the sample point data to Excel.
- Create a DA-Q2 regression relationship in Excel (power trendline) using the paired DA and Q2 values.
- Use the Raster Calculator to create a predicted Q2 raster for the catchment based on the DA raster and the DA-Q2 regression relationship – for example, 0.4007 * Power('DA' , 0.898). Save as 'Q2'.

9. Create branch lines

- Identify all of the branches to include in the model – those with a DA>= 1% of the total catchment DA (Change the symbology of the DA layer to indicate all cells containing DA >= 1% of the total DA to help with this).
- Identify the order of the branches in terms of their catchment area. Use the 'DA' raster. Branch 1 should follow the main stem of the river, from the catchment outlet and then the flow route with the largest contributing area at each confluence. Branch 2 should be the tributary with the largest contributing area and so on.
- Create a feature class for each branch line (Clear selected features; Select all the line segments of a branch from the 'Channels' layer then right click on data set; Data; Export Data; Selected features. Make sure you select all of the line segments for each branch (a new line segment will start after each confluence). Save as 'Branch[Branch Number]_Line'.

10. Run a batch of the 'Extract Branch Values' script (right click on script in ArcToolbox, select 'batch', and set the parameters for each branch) to do the following for each branch

- Dissolve the segments of the branch lines.
- Create measurement points every 50 m along the branch lines.
- Spatial join Mastermap channel width from polygons to measurement points.
- Extract Q2 values from raster to measurement points.
- Spatial join elevation of any nearby contour points to branch measurement points.
- Add X Y coordinates of each point to the attribute table.

11. FOR EACH BRANCH - Manually enter width values for points missing width values

Note: There are missing values because the width values are generated from the Mastermap 'water' features. These features are not consistent close to structures or junctions, where the polygons change category from 'water' features. In addition, narrow streams are not represented with polygons in Mastermap. This means that when the Mastermap data is filtered by 'water' features, some of the points do not have any data joined to them. There is not an easy way to fix this. The centreline can be buffered, but this will not carry an accurate representation of the river width. Fortunately, the majority of the points will have the width information from the Mastermap water feature.

- Start an editing session and open the attribute table for the Branch Points feature class.
- Show just the points with no recorded widths by sorting the features by ascending 'Width', then selecting all those with <Null> for width, then choosing just to show selection.
- Sort visible points by descending Q2.
- Starting with the point missing a width value with the largest Q2, zoom to that point, identify what its width value should be (based on width of channel polygon and

neighbouring points), and manually enter it into the attribute table. Work through the points until you have entered the width value for all of the points that are not in the headwaters (that is, all of the points that were missing width values due to peculiar polygons caused for example, by bridges, rather than the points that were missing width values in the headwaters due to no polygons representing them).

- Copy values of 1.5 into the records for the remaining features (in the headwaters) with no width value.
- Check whether values are appropriate – in particular, check for any points that differ significantly from others along the same branch (spot them by applying a graduated colour symbology) – maybe due to:
    - points around confluences that take widths from incorrect branch of MasterMap polygons or MasterMap polygons that are not divided at confluence
    - points that have incorrectly taken width values from polygons other than the channel
    - fastest way to do this is to open the attribute table, start an editing mode, set the editing table to show selected features only, then select the features in areas of uncertainty, changing those that need to be changed to fit in with those around them
- Stop and save edits.

12. FOR EACH BRANCH - Use Slope Calculator Excel workbook to calculate slopes from contour points and then transfer point data to the 'Stream power indices' workbook:

- Export the attribute table of the branch point feature class as a .txt file (but don't add the .txt extension so it gets recognised as a csv file).
- Open the extracted text file table in Excel as a comma delimited file, make sure the points are correctly sorted from upstream to downstream, then copy and paste the values (Point, Q2, Contour, Width, X and Y) into the appropriate columns of the 'Slope Calculator' Excel workbook.
- Use macro within 'Slope Calculator' Excel workbook to calculate slopes based on contours (after it removes any repeating contours).
- Extrapolate the missing slope values for points that are before the first contour point and after the last contour point (copy and paste the slope values from the adjacent points).
- Delete the final point if it has an artificially large Q2 value due to being on the downstream branch's raster cell.
- Copy the point, Q2, slope and width values into the input sheet of the 'Stream power indices' workbook.
- Add the Branch number for each point and the downstream Branch and Point numbers for the final point in the branch.

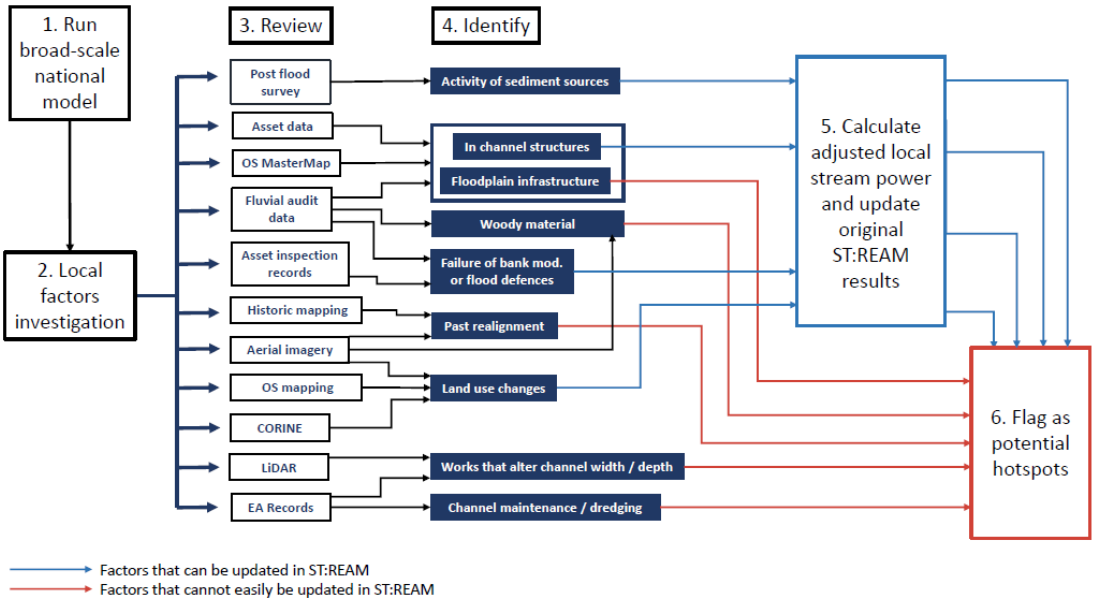
13. Once copied across values for all of the branches… Use 'Stream power indices' Excel workbook to calculate point-based stream power balances

- Add the Branch number for each point and the downstream Branch and Point numbers for the final point in the branch.
- Save as a new version of the 'Stream power indices' in Excel workbook.
- Click the calculate balances button to generate the various stream power balance indices.

14. Use 'ST-REAMv9' Excel workbook to calculate UWSPreach/UWSPupstream reach

- Clear any existing data from the 'ST-REAMv9' Excel workbook.
- Copy and paste the Branch, Point, D/S Branch, D/S Point, Q2, Slope, and Width columns from the 'Slope Calculator' Excel workbook to the 'ST-REAMv9' Excel workbook.
- Save as a new version of the 'ST-REAMv9' Excel workbook.
- Input a value of R to define the sensitivity of the reach boundary hunting algorithm into the appropriate box. The value of R is user-defined but it is recommended that the default value of 0.5 is applied for the initial run and then adjusted for future model runs based on the scale of the user's investigation (increasing the value increases the number of reach boundaries that are identified).
- Press the 'Input Model Data Button'. A series of Visual Basic modules will then divide each branch into a series of functional reaches on the basis of the sequence of stream power per unit bed area values along the branch. For each point of each branch in the catchment the stream power per unit bed area at the 2-year flood (Qmed) is calculated. Then a zonation algorithm is used to divide each branch into reaches with relatively homogenous stream power values. Once the reach boundaries have been identified, the QMED, width and slope values from points across each reach are averaged to define the appropriate values for each reach. The point and reach values for each branch can be viewed by the user in the second 'Model Data' worksheet. The resulting process may take some time (1 to 5 minutes depending on the processing power of your computer, the size of the catchment and the selected value of R).
- Review the point and reach data for each branch in the '2. Model Data' worksheet. The discharge, slope, width and stream power values for each point and each reach within each branch can be viewed on this worksheet. Change the branch that is being displayed using the box and button at the top.
    - Identify whether or not you feel the reach boundaries are appropriate.
    - Identify whether you feel there are an appropriate number of reach boundaries (and if not re-input the data with a different 'R' value).
    - Using aerial photography/field observation, identify whether any of the reaches with stream power values higher than those upstream have completely non-erodible boundaries (for example, concrete lined channels, bedrock gorges) and note the position of those reaches (branch/point number) down.
- Once the user has examined all of the reach-based data they can run the model to calculate reach sediment balances. This is done on the third, '3. Model Output', worksheet. However, first the user should acknowledge whether any reaches have been identified as having non-erodible boundaries. This is done by inputting a Y in the cells corresponding to the reach in question under the '6. Are reach boundaries non-erodible?' column. Then, the user clicks on the 'Run Model' button, which begins a second series of Visual Basic modules that calculate the unit length stream power for each reach on each branch of the catchment. The capacity supply ratio (CSR) for each reach is calculated by dividing the stream power of the reach by the stream power of its upstream neighbour(s). Data and graphs of the supply, capacity and balance for each reach of each branch can be viewed on the third, 'Model Output', worksheet.
- Explore the results that are produced. Two graphs are plotted – one which gives the predicted supply and capacity of each reach in the displayed branch, the other displays the capacity supply ratio for each reach in the displayed branch. You can change the branch for which the outputs are displayed using the box and button on the left-hand side. Do they make sense based upon the reach data explored in the previous worksheet? Compare the results against observations made from the field/aerial photography.
- Copy and paste the values into the relevant column in the 'Stream Power Indices' workbook.

C1.3 Workflow: ST:REAM incorporating local influencing factors



Appendix C2: Method workflow CAESAR-LISFLOOD

C2.1 Background

CAESAR-Lisflood remains largely academic and JBA therefore had no prior experience of this software at the start of this study. Professor Thomas Coulthard (Hull University) generously provided guidance and assistance in using the model and the importance of key parameters. The following section outlines the steps involved in the process of modelling the Kent catchment in Cumbria in CAESAR-Lisflood.

C2.2 Methodology

1. Software download and familiarisation

- Download the software and demonstration files from https://sourceforge.net/p/caesar-lisflood/wiki/Instructions/
- When running in catchment mode, the demonstration is for the Swale catchment.

2. Run with demonstration catchment

- To gain some familiarity with the software, the demonstration catchment was run, and the results reviewed.

3. Run with Kent DEM

- JBA then decided to change one thing, the DEM, leaving all other parameters and rainfall data unchanged.
- It used the DEM for the Kent catchment, experimenting with DEM resolution at the same time.

4. Checks

- After an initial run through of the model with the demonstration files the results were discussed with Professor Tom Coulthard who suggested the following checks at this stage:
    - Removal of 'null data' cells at the outlet of the River Kent (that is, cells with a value of -9999 in the DEM). Water cannot flow into cells with 'null data', which means such cells would impound water at the bottom of the catchment. This problem is circumvented by cropping the DEM so that the river outlet is flush with the edge of the DEM.
    - Removal of tidal areas (n/a in this case).
    - Removal of drained/managed areas (n/a in this case).

5. Crop the DEM to gauge

- Following the checks, the DEM was cropped to the Sedgewick River gauge towards the downstream end of the catchment.

6. DEM resolution

- While resolving the DEM issues discussed above, a range of DEM resolutions were tested (2 m, 10 m, 20 m and 50 m). It was concluded that a relatively coarse grid size of 20 m or greater was required due to run times.

- Subsequent tests on a more powerful computer have shown that the original 7 day run time for 25-years of rainfall data using a 20 m DEM, could be reduced to 2 days.

7. Introduce catchment specific rainfall

- Neighbouring 15-minute rain gauges were identified.
- Rain gauge selection was further refined based on overlapping record length, with the aim of achieving 25 years of rainfall and having this period tie in with the record of river level/flow data.
- Thiessen polygons and associated gauge weights were calculated and used to generate one catchment averaged rainfall time series.
- The model was run using one value for ‘m’, which relates to the run-off rate.
- This revealed some questionable rainfall data (2 hours of greater than 100 mm/hr), which became apparent when comparing the catchment discharge to the recorded flow data.

8. Hydrology calibration

- Once the questionable rainfall values were removed, the model was run with a range of ‘m’ values. These were compared to the recorded flow data, which also forms the downstream boundary for the modelled catchment.
- Five model runs were completed, using an iterative method of determining an appropriate ‘m’ value.
- A value of 0.012 was chosen, which was found to both over and under estimate a few peaks but did not appear to have any clear bias.
- It was decided that peak flow errors were likely to be due to small contributing areas of high rainfall.

9. Manning’s n value

- This relates to the roughness of the channel and controls water level and wave speed/peak flow shape and timing.
- Using the default value 0.040 worked well, so no change was made.

10. River bed grain size

- Up to this point, the model was run using a non-erodible river bed.
- This was achieved by setting the sediment characteristics to those of a 1 m diameter boulder.
- Doing this, the model runs much more quickly.

11. Defining the grain sizes for the river bed

- Ideally, samples of bed material would be collected and analysed for each catchment being modelled.
- For this study, JBA used existing data for the River Cocker and Swindale Beck. It combined these results and used them to provide an indicative data set for the Kent catchment.
- The data consisted of grain size classes for a number of different sites (5 sites for the River Cocker, 7 sites for Swindale Beck).

12. Defining the bedrock layer

- The simplest approach to create a bedrock layer is to ‘offset’ the DEM by a suitable and uniform amount, that is DEM values minus 1.5 m.

- The top of the Kent catchment has a lot of steep sided areas, where a uniform approach to defining the bedrock layer was believed to be inappropriate, JBA therefore applied the following rules:
    - in cells where the slope DEM value is greater than 45 degrees, the bedrock DEM is equal to the 20 m DEM minus 0.5 m
    - in cells where the slope DEM value is less than 45 degrees, the bedrock DEM is equal to the 20 m DEM minus 1.5 m

13. Other advanced considerations for the bedrock layer:

- Unless weirs, erosion control measures, urban areas/roads are added, then these areas will erode, but also sediment control at these locations is NOT accounted for. For example, neither the influence of the weir on downstream sediment transfer, nor the impact of hard boundary protection in cutting off sediment supply, would be accounted for at artificial hard points in the river network.
- Currently the Kent model has NO WEIRS or in channel obstructions/bank protection measures. This will impact sediment movement, scour and deposition areas.
- Thought needs to be given to the DEM resolution, as unless the resolution is fine enough, it may not be practical or a good use of time to introduce this level of information.
- It is tempting to use the finest resolution DEM available, but thought needs to be given not only to run time, but also to how much other information will be inputted into the bedrock layer. This was discussed with Professor Tom Coulthard and he wondered if JBA should be trying the 50 m DEM for comparison (at a future stage) and not the 10 m DEM. His point was that this is a high level 'hot spot' identification study – at least at this stage – and therefore if the same 'hot spots' or areas of interest using the 50 m DEM could be identified, perhaps the focus should be on runtime. For the hot spots/areas of interest, JBA could then revisit these areas in isolation, using a finer resolution DEM and introducing non-erodible objects into the bedrock layer at this stage.

14. Model 'Spin-up'

- JBA was advised by Professor Tom Coulthard to run the model for a couple of years of simulation time, before running the main period to be analysed. Doing this allows excess fines from the initial river bed grain size distribution to be eroded and hard edges or steps in the DEM (usually errors) to be smoothed by the models operation. This was the warm-up phase.
- The outputs from this model run were then used to create the starting conditions for the main model run.

15. Main model run

- Having defined the parameters for 'm' and the sediment distribution.
- The DEM file was replaced with elev.txt.
- The sediment distribution data was replaced by the calculated 'grain.txt'.
- Once the model had completed the 25-year model run, elevdiff.txt is the key output, for defining the scour and deposition zones. This file takes the starting elevations and subtracts the finishing elevations. Therefore, negative values indicate deposition and positive values indicate erosion.

16. Viewing the results

- The elevdiff.txt file can be viewed using GIS software.

The results can be normalised to different resolutions. This has been tested and results are described in Appendix C5.

Appendix C3: Method workflow: Half-yield method

C3.1 Background

The half-yield method is a new technique developed by Dr Philip Soar for this project. The overview of the methodology is presented in section C3.2 below, and described in detail in C3.3.

Dr Philip Soar coded the half-yield method in VBA in an Excel spreadsheet as a standalone model, designed to apply the method on each RHS survey point one at a time. JBA Consulting created a command prompt 'front end' which enables the code to batch process multiple RHS survey points. The software accepts a series of Excel spreadsheets as inputs, including a combined input data spreadsheet for the cross section parameters (width, depth), a flow duration data input sheet (containing the FDC ratios and the gauge data) and the half-yield method spreadsheet. The user selects an output folder to which the output CSVs are written. The following section outlines the steps involved in applying the method to the test catchments.

C3.2 Methodology

The following steps outline the approach taken to apply the half-yield method to the 3 trial catchments:

1. Delineate contributing area catchments for each of the RHS survey points

Following the steps below will create a catchment for each of the RHS survey points:

- Terrain Pre-processing:
    - In the ArcGIS Hydrotools toolbox, select the Data Management Terrain Pre-processing tool in the Terrain Pre-processing tab and set the tags for the themes used in the Terrain Pre-processing menu.
    - The DEM manipulation tab includes a group of functions for manipulating the DEM grid, including burning, fencing and filling. In DEM Reconditioning, burn the DRN into the DEM using a sharp drop of 20. This value may need to be adjusted for each catchment. This step 'forces' the DRN onto the DEM. All of the steps below are necessary to delineate the contributing area catchments for each of the RHS survey points.
    - Flow direction: create a flow direction grid from the DEM grid.
    - Flow accumulation: create a flow accumulation grid from the flow direction grid.
    - Stream definition: create a new grid (stream grid) with cells from the flow accumulation grid that exceed a user-defined threshold.
    - Stream segmentation: create a stream link grid from the stream grid in which each link between 2 stream junctions gets a unique identifier.
    - Catchment grid delineation: create a catchment grid for a link grid.
    - Catchment polygon processing: create catchment polygons out of the catchment grid.
    - Drainage line processing: create catchment polygons out of the catchment grid.

- Adjoint catchment processing: create adjoint catchment polygon for each catchment in the catchment polygon feature class. Adjoint catchment is total upstream area (if any) draining into a single catchment.

- Watershed processing:
    - Batch watershed delineation: delineate the contributing area catchments by setting the batch points to the RHS survey points.

2. Calculate a FDC for each of the RHS survey points by pro-rating the gauged FDC

Following the steps below creates a FDC for each of the RHS survey points:

- In the Low Flows 2 software:
    - load the contributing area catchment for each RHS survey point into Low Flows 2
    - load the catchment for each of the gauges used. Gauges were considered to be suitable if they had a long record and had gauged daily flows available for download
    - generate an FDC for the RHS catchments and the gauge catchments
    - export the catchment data to an Excel spreadsheet
- In Excel:
    - For each RHS survey point establish which is the closest gauge.
    - Calculate the ratio between the RHS survey point FDC and the gauge FDC, for each flow percentile.

3. Extract input parameters from the RHS data set

- The following are extracted from the RHS spreadsheet using a script programmed in python:
    - river width
    - left bank height
    - right bank height
    - water depth
    - modal descriptive bed material from all 10 values given for survey. The modal descriptive bed material is then mapped to a representative grain size. For example, ‘Gravel’ is given a grain size of 9 mm (midpoint of gravel range 2 to 16 mm).
- River gradient is extracted from the DRN, using an algorithm to extract the gradient from the DRN polyline closest to the RHS survey point.

4. Pass the input parameters and the FDC ratios to the software for processing

5. Create shapefiles of results using the CSV data outputs

C3.3 Background to method development

The aim was to explore whether an approach could be developed that is conceptually simple and suitable for employing at the catchment scale for alluvial channels. This would be based on sound theoretical underpinnings related to sediment transport and channel stability, potentially straightforward to code and, critically, flexible in accounting for climate change. Ideally, such a method would need to be based on readily available data sets where possible/practical and with fully justifiable assumptions. The preferred method would not require a backwater model or reach delineation and, in treating sites independent of other locations or reaches in the river system, would represent a credible alternative work flow to existing accounting methods based on balances in sediment transport between contiguous reaches.

C3.4 Conceptual development

The proposed conceptual model comprises 2 stages of assessment:

Stage 1: Channel performance (p)

The sediment transport capacity of the subject channel is compared with the sediment transport capacity of a theoretical regime channel, according to a capacity-regime transport ratio:

$$CRR = \frac{Y_s}{Y_r}$$

Where Y_s = sediment yield of the subject channel, based on a representative cross section for the subject reach; Y_r is the sediment yield of the hypothetical regime channel. Y_s and Y_r are assumed to reflect a period of years (or average annual yield over the long term).

This approach bears similarities to both ST:REAM (Parker and others, 2015) and REAS (Soar and others, 2017) and follows the capacity-supply ratio concept inherent in the methodologies of Soar and Thorne (2001) and Stroth and others (2017).

Sediment yield, Y, is calculated based on standard magnitude-frequency analysis (Biedenharn and others, 2000; Soar and Thorne, 2011, whereby:

$$Y = \sum_{i=1}^{k} (Qs_i \times F_i)$$

Where Qs_i = the sediment yield corresponding to class discharge Q_i with decimal frequency of occurrence F_i (in the flow frequency histogram of k classes).

The theoretical regime channel dimensions are derived based on two assumptions:

i) stable bankfull width conforms to the general form of the downstream hydraulic geometry (regime) equation:

$$W = aQ_b^{0.5}$$

Where Q_b = bankfull discharge; a = constant (related to channel type)

ii) the bankfull discharge equals the half-load discharge, Q_h, in stable alluvial rivers with mobile beds:

$$Q_b = Q_h$$

The half load (or half-yield) discharge is a variant of the 'effective discharge', Q_e, derived using standard magnitude-frequency analysis (see Emmett and Wolman, 2001; Vogel and others, 2003; Klonsky and Vogel, 2011; Sholtes and Bledsoe, 2016). Whereas Q_e is the 'unique' discharge that transports the most sediment over time, the half-load discharge, Q_h, is the discharge associated with 50% of the cumulative sediment load (Y_{50}, or C=0.5) (Figure 2-1). As Q_h is measured from the cumulative distribution, it is a more robust measure than the effective discharge and has been found to be a reliable 'process-based' estimator of bankfull discharge in stable river channels (for example, Sholtes and Bledsoe, 2016).

The assumption, then, is that Q_h (at C=0.5) approximates the bankfull discharge, Q_b, in stable alluvial channels with mobile beds (stable in terms of sediment transport continuity and therefore channels where their morphologies are 'in regime'). Satisfying these criteria (using model iteration) enables the bankfull discharge, regime bankfull width and average bankfull depth to be derived (assuming constant slope).

The quotient Y_s/Y_r indicates deviation from equilibrium sediment transport, sensitivity to change and therefore stable channel morphology, such that $Y_s/Y_r>1$ for channels more likely to exhibit erosional behaviour and $0=<Y_s/Y_r<1$ for channels more likely to exhibit depositional behaviour. A 'performance' factor, P, can be defined as:

For $CRR > 1$ $\qquad P = 1 - CRR$

Generating P<0 (erosional behaviour).

For $0 \leq CRR < 1$ $\qquad P = (1/CRR) - 1$

Generating P>0 (depositional behaviour).

Therefore, P takes a value of zero for regime channels where $Y_s=Y_r$, positive values indicate erosional behaviour and negative values suggest depositional behaviour would predominate. A suitable performance threshold ($\pm P_t$) could be used to identify stable channel reaches where sensitivity to change is not significant (for example, $P_t=1$ would refer to channels with sediment yields that are within 0.5 and 2.0 times the regime yield; $P_t=0.5$ would refer to channels with sediment yields that are within 0.67 and 1.5 times the regime yield; $P_t=0.25$ would refer to channels with sediment yields that are within 0.8 and 1.25 times the regime yield).

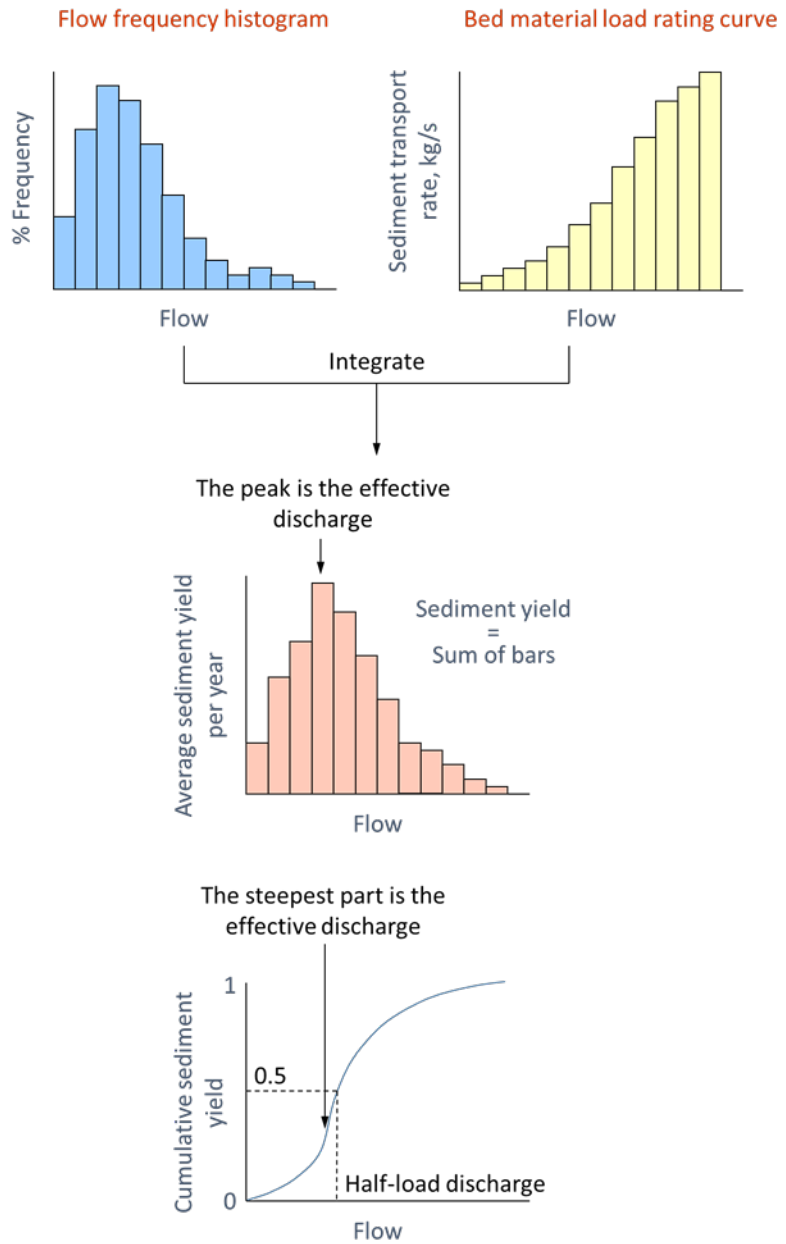


Figure C3-1 Calculation of sediment yield, effective discharge and half-load discharge

Stage 2: Channel effectiveness (E)

Channel 'effectiveness', here, differentiates between the geomorphological performance of in-channel flows and bank overtopping flows and therefore provides an indication of the significance of flood flows on the long-term sediment yield. This is achieved by analysing the cumulative sediment yield (decimal contribution to the long-term sediment budget), C.

Where the measured overtopping discharge, Q_o, corresponds to a value of C that deviates markedly from 0.5 (at the half load, Y50), this suggests that either flows above or below the overtopping level are predominantly responsible for the total load. Therefore, a method that measures how close the overtopping discharge Q_o corresponds to C=0.5 'might' provide an appropriate guide to the type of flows that are performing the majority of the work in transporting sediment (Figure C3-2 and Figure C3-3).

An effectiveness index, E, can be defined as:

$$E=1-2C_o$$

Where E (E: -1<=E<=1) represents the balance between in-channel and overtopping discharges on transporting sediment; C_o = proportion of the cumulative sediment load (0 to 1) corresponding to the overtopping discharge, such that:

- E=0 when the channel geometry is 'optimised' to convey the imposed sediment load, with 50% of the load transported by within-channel flows and 50% of the load transported by overbank flows. At this condition, the overtopping discharge, Q_o equals the half load discharge Q_h. This does not necessarily mean that the channel is in sediment transporting equilibrium with regime channel geometry.
- -1<=E<0 when the majority of the sediment load is conveyed by discharges that do not overtop the banks. This condition suggests that in-channel discharges are responsible for performing most work in transporting sediment and might indicate a channel that is too deep and/or wide for the imposed sediment transport regime. E=-1 for channels that transport all of its sediment by in-channel discharges.
- 0<E<=1 when the majority of the sediment load is conveyed by discharges that overtop the banks. This condition suggests that overbank discharges are responsible for performing most work in transporting sediment and might indicate a channel that is too shallow and/or narrow for the imposed sediment transport regime or inability to mobilise coarse sediment by low flows. E=1 for channels that transport all of their sediment by overtopping discharges (therefore, no discernible channel morphology or armoured bed).

The flow regime might be considered to be balanced (morphologically) if, at the overtopping discharge, E lies between some user-defined threshold, ±Et (for example, -0.25 to 0.25, or -0.5 to 0.5).

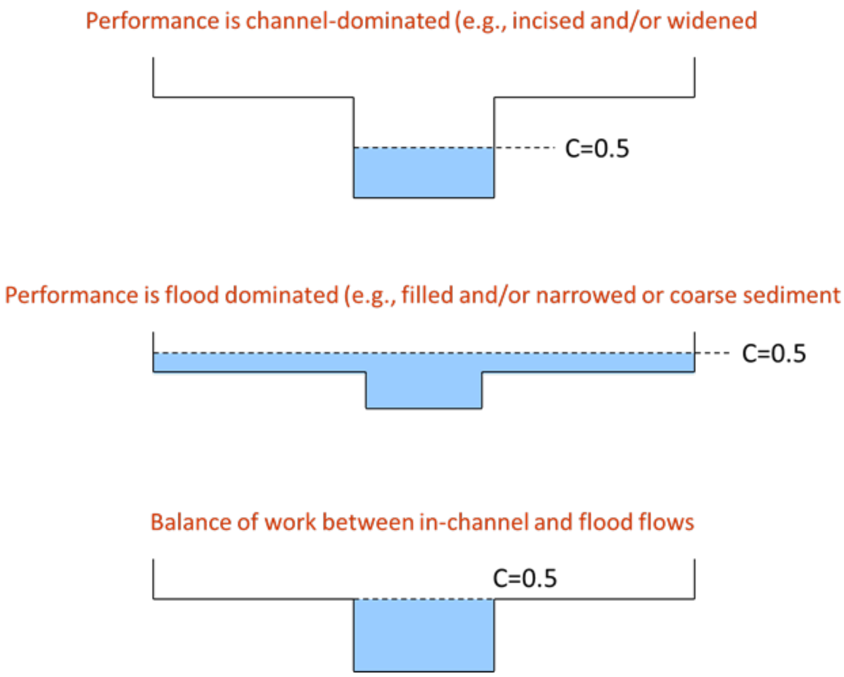


Figure C3-2 Water surface elevation of the half-yield discharge with respect to channel and flood plain morphologies

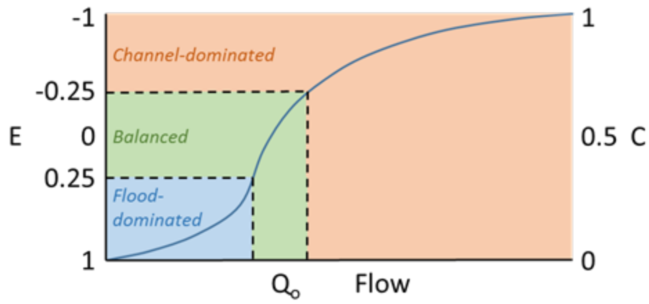


Figure C3-3: Sediment transporting 'effectiveness' (E) of the channel geometry related to the proportional contribution (C) of the overtopping discharge (Q_o) to the long-term sediment yield.

For illustration, differentiation is made between channels that transport sediment predominately by in-channel flows (channel dominated), overtopping flows (flood-dominated) and those that balance the work performed between in-channel and overbank flows (balanced) according to an effectiveness threshold shown for E=±0.25.

C3.4 Interpretation

Critical: The effectiveness index, E, alone does not provide an adequate indicator of channel sensitivity (erosional or depositional behaviour). This is particularly the case for channels with mobile gravel/cobble beds. It can be shown that as sediment size increases and therefore the critical discharge for entrainment increases, the half-load discharge also increases. Therefore, the condition Qo=Qh (overbank discharge equalling the half-load discharge) must be satisfied with larger and larger cross-sectional areas as sediment size increases. For the hypothetical case of an unstable channel due to excessive widening, it is plausible that Qo=Qh can still be satisfied if sediment size is large enough (albeit with probably very small total sediment yield). This finding has an important implication in the context of the research by Sholtes and Bledsoe (2016) in that if Qb approximates Qh in stable gravel-bed rivers (as they demonstrate based on empirical data) then the cross-sectional area of stable gravel-bed rivers must increase as sediment size increases. Therefore, coarse beds must exhibit larger channels than sandy beds (as a general condition) for the premise Qb=Qh to hold true.

Model stages 1 and 2 generate a matrix of possible outcomes with indicative interpretation as follows:

Performance Factor, P	Effectiveness Index, E: $-1 \le E < -E_t$	$-E_t \le E < E_t$	$E_t \le E < 1$
$P_t \le P$	**Depositional** • Wide (possibly incised) • In-channel flows dominant • (Frequent flows most effective at depositing) • Bar-berm building (possibly bed raising)	**Depositional** • Wide/shallow and/or coarse sediment • Balance in sediment yield between in-channel and overtopping flows • Bar-berm building	**Depositional** • Wide/shallow and/or coarse sediment • Flood flows dominant • (Infrequent flows most effective at depositing) • Bar-berm building • Possible deposition of fines
$-P_t \le P < P_t$	**Stable – depositional** • In-channel flows dominant • Incised/recovering • (Frequent flows most effective at depositing) • Gradual bed raising	**Stable** • Balance in sediment yield between in-channel and overtopping flows	**Stable – erosional** • Undersized channel and/or coarse sediment • Flood flows dominant • (Infrequent flows most effective at eroding) • Bed scour • Possible deposition of fines
$P < -P_t$	**Erosional** • Narrow/incised (signif) • In-channel flows dominant • (Frequent flows most effective at eroding) • Bank erosion	**Erosional** • Narrow/incised • Balance in sediment yield between in-channel and overtopping flows • Bank erosion	**Erosional** • Narrow/shallow and/or coarse sediment • Flood flows dominant • (Infrequent flows most effective at eroding) • Bed scour/bank erosion • Possible deposition of fines

Figure C3-4 Indicative interpretation of results

Based on: performance factor, P, scores relative to a performance threshold for equilibrium sediment transport, Pt, in combination with effectiveness index, E, scores relative to a user-defined effectiveness threshold, Et, measuring the deviation of the overtopping discharge from the half-load discharge.

C3.5 Model assumptions

- The model user is required to specify the coefficient in the width hydraulic geometry equation. This is widely known to vary between stream types and exhibit natural variability (Soar and Thorne, 2001) and therefore introduces some uncertainty, which could have a significant impact on results. Representative values can be given for gravel-bed and sand-bed rivers. The coefficient could be used as a calibration factor against known stable or unstable sites.
- Sediment transport is calculated using the Lammers and Bledsoe (2018) equations for bedload and total load, both based on specific stream power. If the d_{50} of the bed material is greater than 2 mm, the bedload equation is applied, otherwise the total load equation is applied. 'Actual' load, though, is not an output of the model – the equations are used to derive the performance factor, P, and effectiveness index, E. The equations are presented and simplified to a general model for practical application in the Appendix.
- Rectangular cross sections are assumed for the main channel (width and depth).
- Flow duration curves must be synthesised for each site. The obvious choice here is to use the LowFlows software.
- Sediment load is considered for the flow area over the bed of the main channel only. The model removes overbank flow contributions using the conventional

divided channel approach for compositing discharge. This requires user-defined Manning n values for the main channel and overbank area.

- Depth is needed in the model, but if unavailable then the theoretical regime depth can be assumed. The default data set for consideration is the RHS and to run the model for sites in the database only.
- ‘Representative’ sediment size is required. Options include RHS or to have representative sizes for different.
- ‘Representative’ Manning n values are required for main channel and overbank area. Options are available to generate Manning n values for channel and flood plain based on CES or even to have representative values for different channel types.
- Slope is held constant in the model, therefore ‘stable’ refers to equilibrium sediment transport at the governing slope. The derived regime cross sections assume existing slope values. The inability to suggest likely morphological adjustments on the basis of gradient and planform remains a limitation of this approach. An improvement might be to derive a suite of outputs at each location of interest for a set of sinuosities to reflect hypothetical regime planforms.

An advantage of this approach is that each site (cross section) is treated independently and on its own merit. A backwater model is not required. Linking cross sections in a network system is not required. Regular spaced locations are not critical. The method is used ‘where’ data exist, for example, at RHS sites. Therefore, this method differs from others in that it rests on at-a-site performance in transporting sediment rather than difference or quotient in actual load (or proxy such as stream power or total energy) between contiguous reaches.

The method overcomes some of the limitations/assumptions of accounting system methods such as ST:REAM. Reach delineation is not required. A stream power threshold is not required for classifying unstable locations. The flow duration curve is intrinsic to the method (incorporating the impact of the high mag, low frequency events), revealing the relative importance of in-channel versus flood flows, and there is scope for adjusting the flow regime to account for climate change. However, in doing so, the method introduces new premises and issues regarding data procurement.

Sediment supply is implicitly accounted for in the measures of performance, P, and effectiveness, E. Deviation from zero reflects previous and, potentially, ongoing discontinuity between sediment supply and transporting capacity as manifested in the channel morphology (notably, how the width and depth differ from the regime geometry). Is this approach well suited for locations where sediment transport is significantly impacted by local controls (bridges, weirs, traps)? Conceivably, P and E should be influenced by upstream and downstream controls if the channel geometry has adjusted partially or fully to the imbalance between supply and capacity.

Appendix C4: Method workflow: Shear stress data mining method

C4.1 Background

The SSDM approach seeks to make use of existing large scale, high resolution national flood mapping data sets. The modelling generated for the Environment Agency risk of flooding from surface water (RoFSW) maps produced detailed 2 m resolution depth and velocity information with national coverage for a range of probability events (0.1%, 1% and 3.33% annual exceedance probability (AEP)), which have been used with the SSDM approach for this study.

Input data: risk of flooding from surface water model

The depth and velocity grids were produced using a direct rainfall and 'ReFH losses' approach, whereby net rainfall was estimated in relation to local hydrology, and a 2D flood inundation model, JFlow ® was used to route the resulting flows over a 2 m resolution raster.

The peak depths and velocities were computed through the rainfall event, the accuracy of which is very dependent on the accuracy of the 2 m uFMfSW merged DTM and the representation of the channels and flow accumulation pathways within the DTM. The 2012 DTM which was used comprised 2 m resolution LiDAR (RMSE ~ 0.15 m in the vertical) where available (mainly in urban areas on large rivers), mosaiced into 5 m Nextmap Britain SAR data (RMSE can be ~ 1.0 m in vertical), also resampled to 2 m.

Relatively short duration (1, 3, 6 hour) summer storm profiles were used over 5 km tiled domains, and then mosaiced together for each probability to produce the RoFSW probability maps. This does mean that the events were chosen for localised convective/summer rainfall profiles, and that the flows on large watercourses will not have the larger flow accumulations associated with flood-critical storms on large fluvial systems. Nonetheless, the events still represent a consistent 'loading' on the system, allowing shear stresses capable of erosive action to be compared.

Applying the shear stress data mining approach

Data mining of 2 m resolution hydraulic data to understand the distribution of shear stresses and likely sediment erosion risk had not knowingly been carried out on a national scale when this report was produced.

Similar approaches have been used based on reusing 2D modelling outputs, with validation against field data (Reid and others, 2018), and physics-based formulations of erosion potential have been used for some time (for example, Lane and others, 2005). The Reid and others, 2018 paper showed a similar shear-stress based approach (derived from 2D model outputs) was useful in understanding gravel bar evolution when combined and compared with very high resolution terrestrial LiDAR.

The SSDM approach used here relies on an efficient ArcGIS model builder code that computes local shear based on average velocity, depth and roughness. This is compared with critical shear stress for entrainment and erosion, using 3 assumptions on deposition, erosion and sediment grain size distribution. It results in a zonal classification of sediment erosion, transition/transport and deposition, which can be computed for a range of assumptions. The zones have been produced for 2 example AEP surface water maps corresponding to 3.33 % and 1% AEP, both assuming a D50 of 50 mm, a Manning's roughness of 0.05, and a Shields constant of 0.6.

The model takes approximately 12 hours to run nationally, which means that it would be straightforward to generate a scenario-library based on a range of assumptions and select outlines that are more appropriate depending on local-conditions. This would be helped by using a national grain size distribution data set if this becomes available in the future.

C4.2 Input data

The following national data sets have been used:

- National DTM (for example, uFMfSW2012)
- uFMfSW (RoFSW) complex model outputs
- continuous rasters of depths and velocities. These are maximum mosaics across the national 5 km tiles and across 3 storm durations (1, 3, 6 hour), for each of 3 probabilities (0.1,1,3.33% AEP)
- Landcover - LCM2007 or CORINE2012 with landcover/roughness look up assumption
- OS Terrain and Slope based on this 50 m grid
- The slowly permeable soils layer from the open data mapping outputs of the Working with Natural Processes project (see Hankin and others, 2018). This is based on the BGS superficial geology 'till-diamicton' layer, but with areas of woodland removed. It is used here to represent sources of erodible material.

To avoid boundary changes in roughness and therefore shear stresses, a constant Manning's roughness of 0.05 was used to understand the effect of the other assumptions/variables within these initial analyses.

C4.3 Method

Shear stress can be derived from a quadratic expression in relation to velocity given in equation (1):

(1) $pgn^2U^2/d^{1/3}$

This gives desirable properties for shear in relation to depth and depth averaged velocity and generates similar values to that of an assumed logarithmic profile. This quadratic equation can then be used and compared against critical shear stress to identify where erosion is more likely. Manning's roughness can be estimated based on land cover, although here it has been set at a constant 0.05 value to allow a greater understanding of how the other variables influence shear stress distributions and to avoid sudden changes at boundaries. A fully variable roughness dependent on land cover could be used if the method is taken further.

With an estimate of average depth, depth-averaged velocity and Manning's roughness, it is possible to estimate shear stress distribution.

Other variables include:

- D50 = 0.05 (Can be based on land cover when scenario library is built up)
- Shields constant = 0.06 (The literature varies between 0.03 and 0.06. To be considered if scenario-library is built up)
- Deposition factor = 0.3

The ArcGIS model builder code (Figure C4-1) is easy to adapt (or translated to python) and has been used experimentally on smaller catchments. This formulation was originally developed by Kate Bradbrook of JBA, but has been adapted, for instance changing some of the fixed variables to rasters to experiment with variable D50, Manning's and so on.

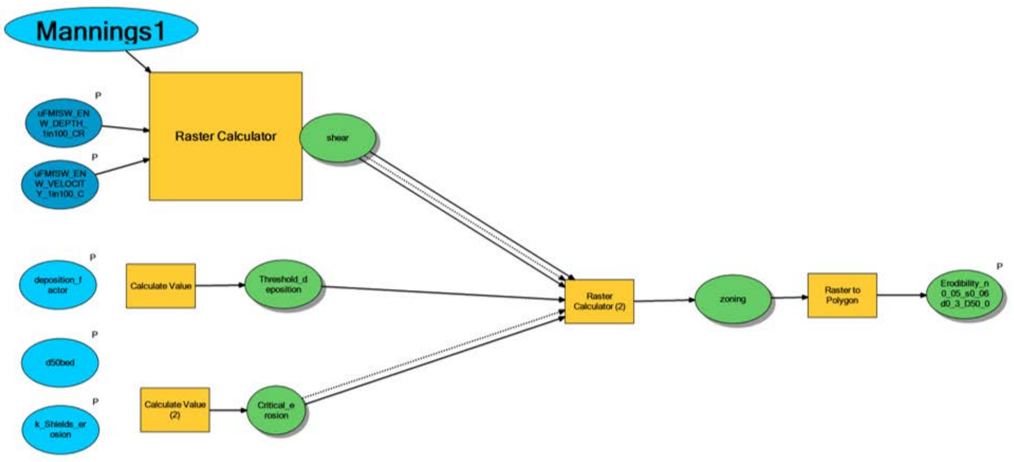


Figure C4-1 Sediment Risk Schematisation in ArcGIS Model Builder

C4.4 Majority filtering

The majority filtering[1] technique was explored to remove rapid spatial variations and isolated islands of one particular type. The ArcGIS has different settings, but here we use the simplest default setting, whereby isolated cells are changed to the value of the majority of cells that surround it. This is explained pictorially in Figure C4-2.

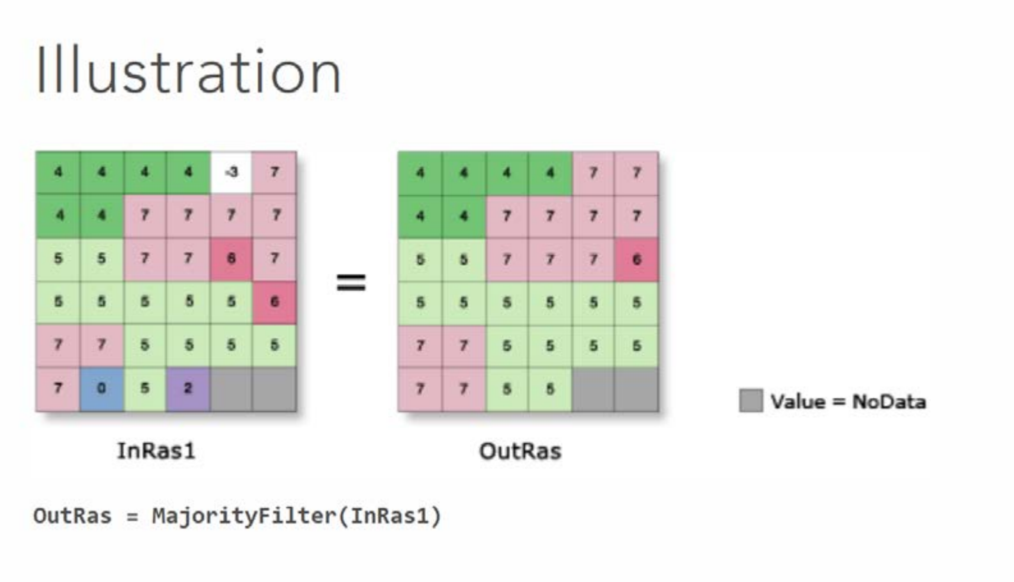


Figure C4-2 ArcGIS Majority Filter

1 http://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/majority-filter.htm

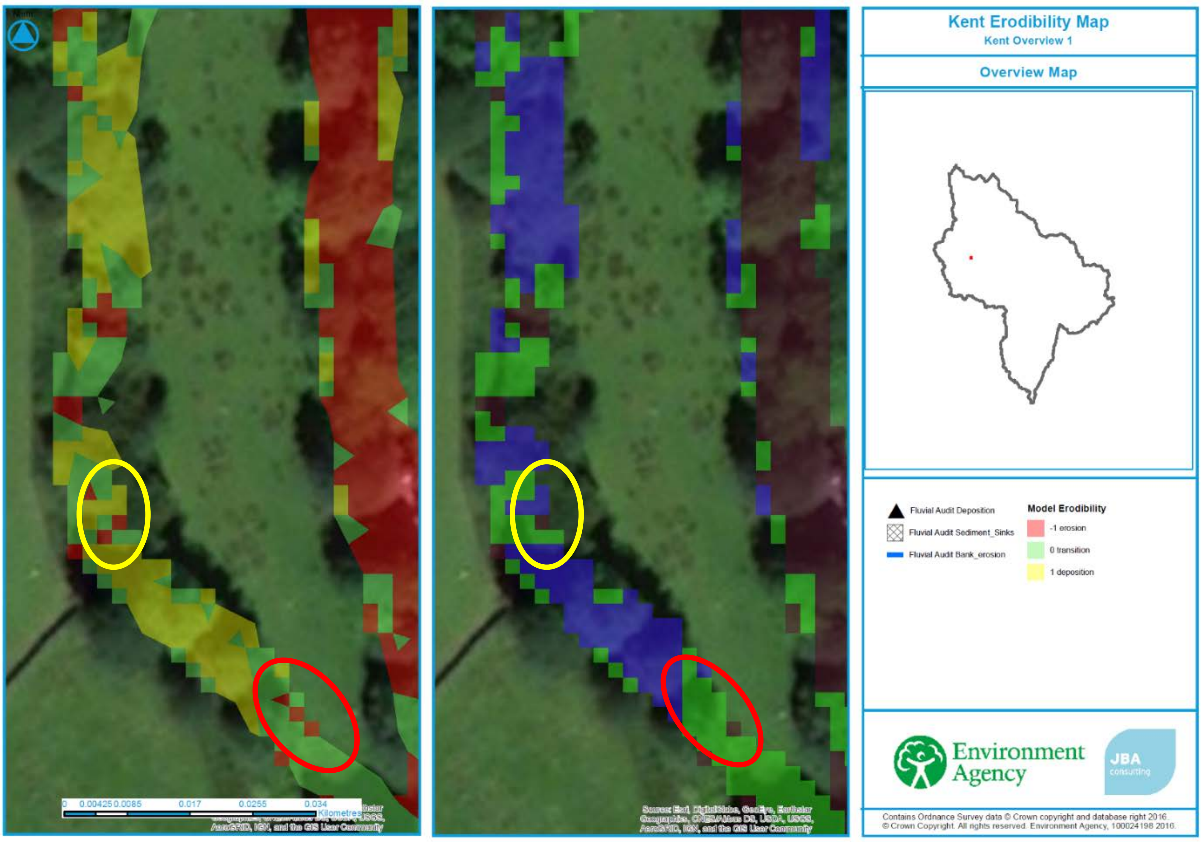


Figure C4-3 ArcGIS Majority Filter (LHS is unfiltered, RHS is filtered)

Figure C4-3 highlights a potential problem with this filtering approach. While the methodology removes areas of rapid change that might dampen the oscillation between shear stresses meeting a threshold and not (yellow ellipses), it unfortunately also removes areas of high shear stress near the river bank, which have been found to tally with fluvial audit observations (red ellipses). The isolated high shear stress values are therefore shown to be valuable in some cases.

Appendix C5: CAESAR-Lisflood normalisation

C5.1 Overview

An investigation has been carried out into ways in which the CAESAR-Lisflood results can be normalised to provide a more user-friendly data set for end users. CAESAR-Lisflood outputs data in the form of a raster grid of elevation differences (m), with negative values indicating deposition and positive values indicating erosion. A method has been developed to sample the CAESAR-Lisflood data within a 50 m radius of the channel network. A buffer with a radius of 50 m has been applied to the river network points created for the ST:REAM methods testing. In Figure C5-1 below, the ST:REAM river network points are represented with black points and the buffers are represented with red circles. The underlying CAESAR-Lisflood results have been sampled within each buffer. Each buffer circle contains 21 cells. A range of statistics for the cells within the buffer have been extracted, including:

- mean (m) – average value of the 21 cells within the buffer
- minimum (m) – minimum value of the 21 cells within the buffer
- maximum (m) – maximum value of the 21 cells with the buffer
- standard deviation – standard deviation of the 21 cells within the buffer
- range (m) – range of 21 cells within the buffer
- majority – classification of the buffer into a specific class according to the majority of the cells of each class within the buffer. The classes are: 1=deposition (<-0.1 m elevation change), 2=stable (<-0.1 m and >0.1 m elevation change) and 3= erosion (>0.1 m elevation change)

Example statistics for the buffers indicated by the numbered arrows in Figure C5-1 are shown in Table C5-1.

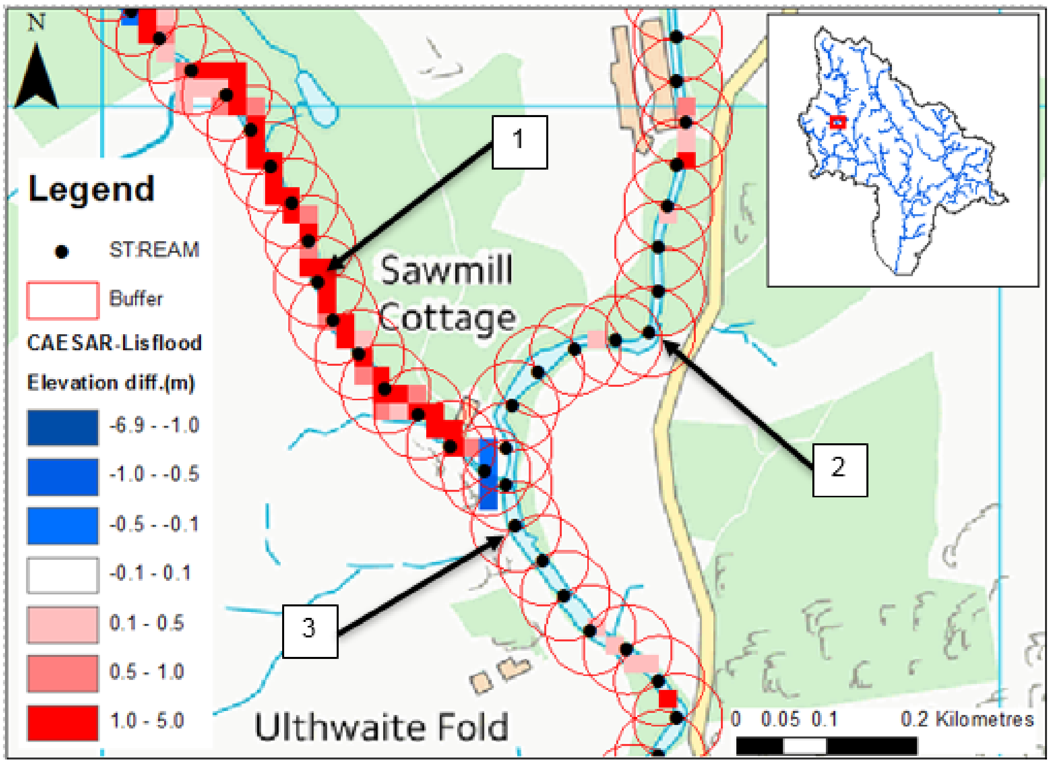


Figure C5-1 Buffer circles used to extract statistics from CAESAR-Lisflood results

Table C5-1 Example statistics from the numbered buffer circles in Figure 1-1

Number	Minimum	Maximum	Range	Mean	STD	Sum	Majority
1	-0.005	1.457	1.463	0.533	0.588	11.188	2 (stable)
2	-0.007	0.058	0.064	0.002	0.012	0.041	2 (stable)
3	-0.550	0.024	0.575	-0.025	0.118	-0.531	2 (stable)

Investigation has shown that normalising the results using the mean value within the buffer circle appears to represent the geomorphological processes relatively well. Examples are shown below in Figure C5-2, Figure C5-3 and FigureC5-4 in which the normalised results are plotted against the original CAESAR-Lisflood results at spot check locations Kent_01, Kent_02 and Kent_03, respectively. The normalised results are coloured according to the mean value, with 1=deposition (<-0.1 m elevation change), 2=stable (<-0.1 m and >0.1 m elevation change) and 3=erosion (>0.1 m elevation change).

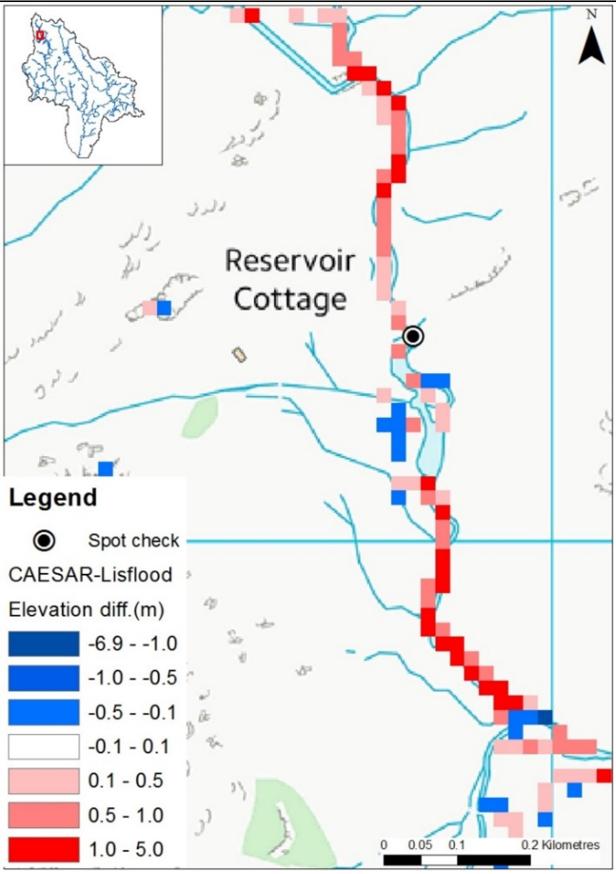
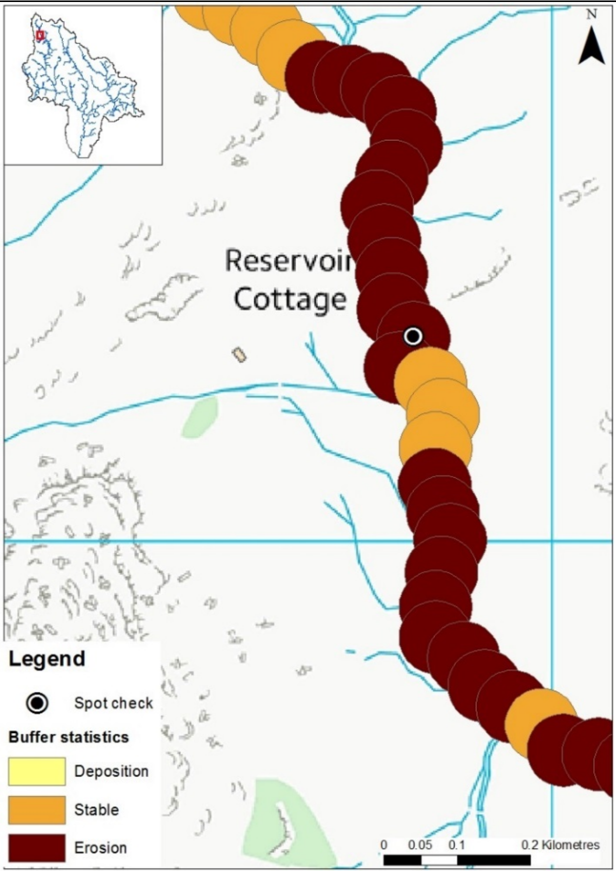
<table>
<tr><th>CAESAR-Lisflood</th><th>Normalised CAESAR Lisflood results</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Original CAESAR-Lisflood results - the reach is generally erosive, with a small area of deposition/stability in the vicinity of the lake.</td><td>The main processes are still captured within the normalised results, with the reach generally classified as erosive, with an area of stability in the vicinity of the lake.</td></tr>
</table>

Figure C5-2: Comparison of CAESAR-Lisflood results and normalised CAESAR-Lisflood results at spot check location Kent_01

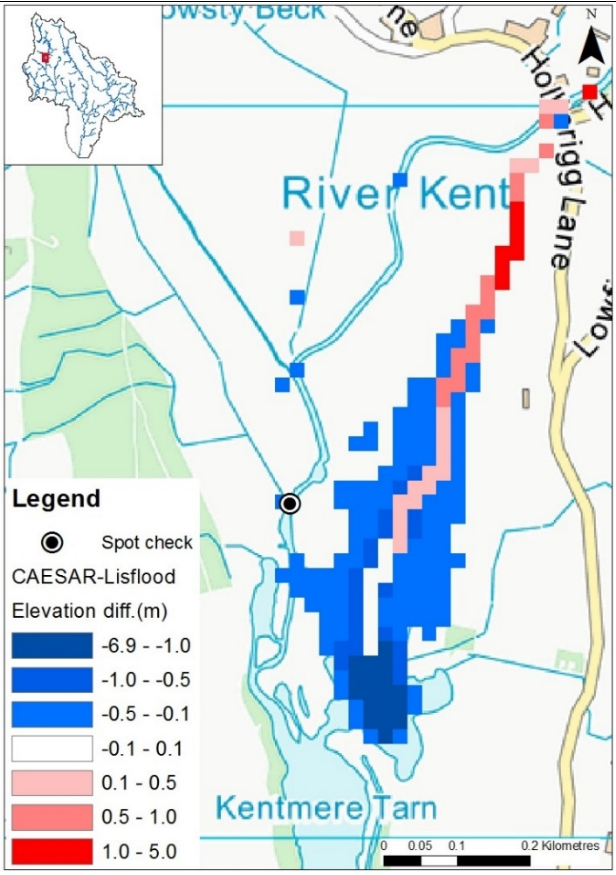
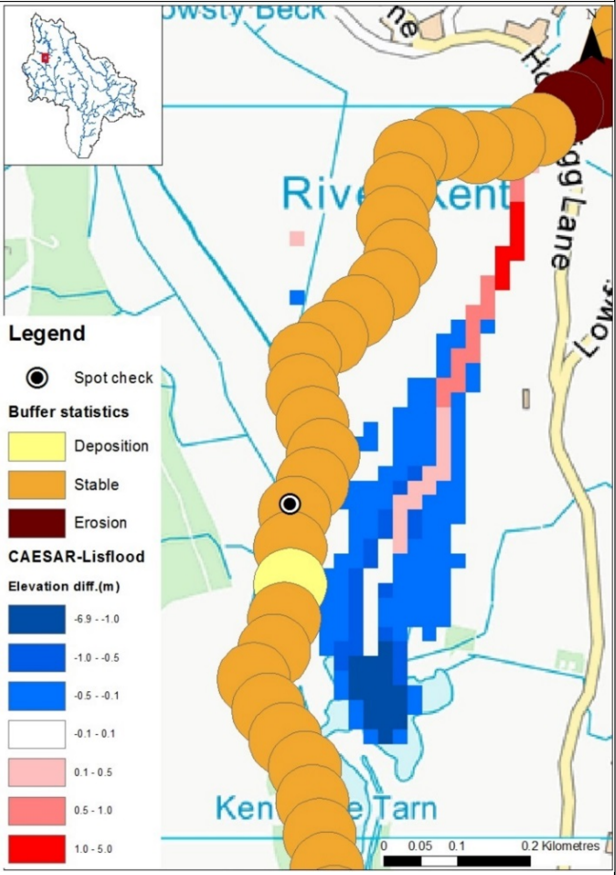
<table>
<tr><th>CAESAR-Lisflood</th><th>Normalised CAESAR Lisflood results</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Original CAESAR-Lisflood results – due to the perched nature of the channel in this location, coupled perhaps with the coarse resolution of the DTM used, the modelling results do not follow the existing channel route.</td><td>Due to the perched nature of the reach, there is a mismatch between the existing channel network and the modelled results.</td></tr>
</table>

Figure C5-3 Comparison of CAESAR-Lisflood results and normalised CAESAR-Lisflood results at spot check location Kent_02

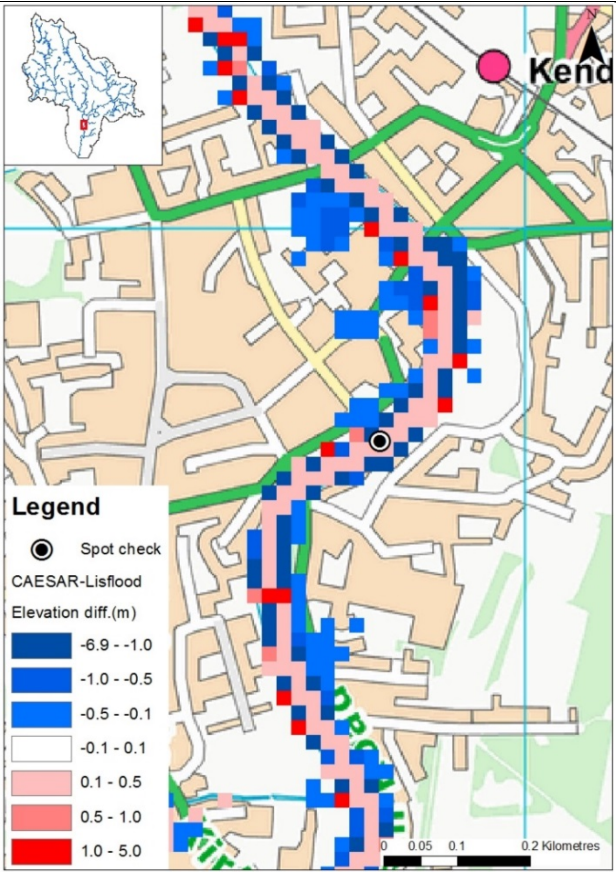
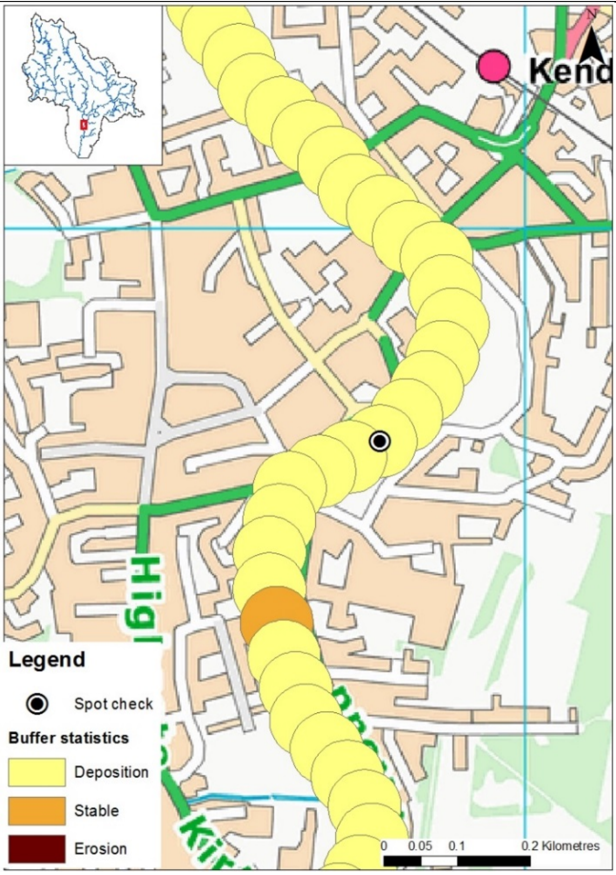
CAESAR-Lisflood	Normalised CAESAR Lisflood results
	
Original CAESAR-Lisflood results - the reach is classified as erosional (minor), with lateral deposition.	The detail of in-channel erosion has been removed from the normalised results, however the magnitude of erosion is only deemed to be minor (only 0.1 to 0.5 m elevation change) so the dominant processes of deposition are still represented in the normalised data set.

Figure C5-4 Comparison of CAESAR-Lisflood results and normalised CAESAR-Lisflood results at spot check location Kent_03

C5.2 Discussion

This initial investigation has shown that it is possible to simplify the outputs from CAESAR-Lisflood in a meaningful way. The technique relies on a series of points spaced along the channel network, to which a buffer is applied to create a polygon that can be used to query the underlying CAESAR-Lisflood results. This allows the raster grid results to be normalised into a set of statistics for each data point along the channel network.

The technique relies on the CAESAR-Lisflood modelled outputs being aligned with the existing channel network, which is not the case in several locations in the test catchment where historic channel modification has altered the channel course.

Using only the mean value from the available set of statistics means that the method will be prone to misinterpretation when more than one process (erosion and deposition) is occurring within a single area. In these areas, it is likely that the values will cancel out to some extent, resulting in a mean value that falls within the 'stable' band. This could perhaps be rectified by considering the standard deviation in combination with the mean value. The standard deviation is likely to be higher for areas classified as stable, but with a range of erosion and deposition processes, compared to those areas classified as stable, with a lack of major erosion or deposition.

To illustrate this point, 2 locations are compared in Figure C5-5 and Figure C5-6 below. The reach displayed in Figure C5-5 has 2 areas exhibiting both erosion and deposition processes (circled). According to the mean value of the cells in the corresponding buffer areas, these areas are classified as stable, with a mean elevation change between -0.1 m and 0.1 m. The standard deviation of the cells in the buffer areas classified as stable are shown in the right-hand plot, varying between 0.29 to 0.72.

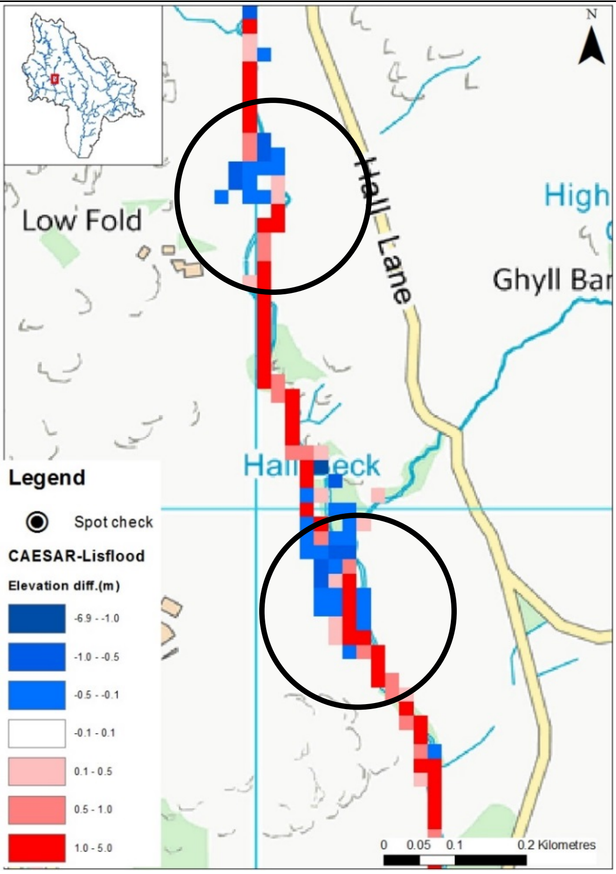
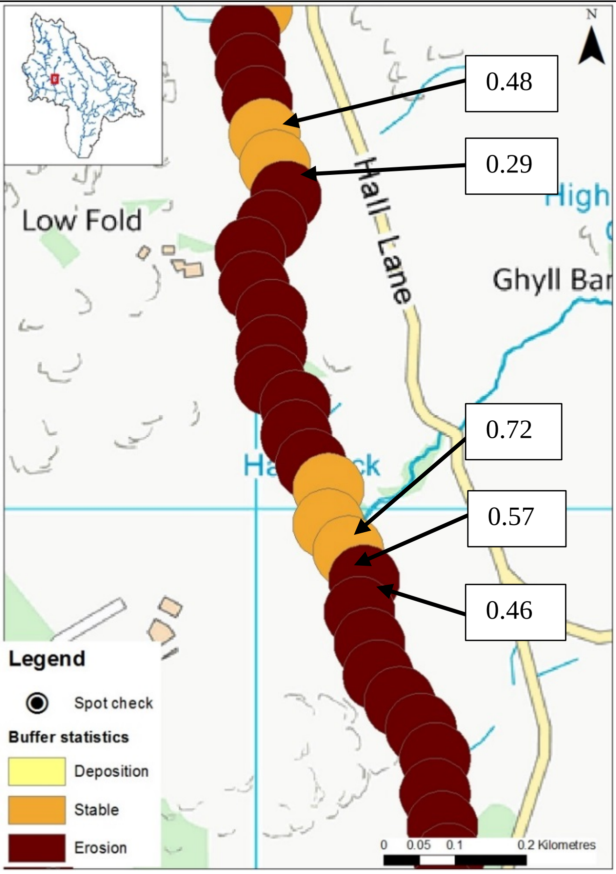
<table>
<tr><th>CAESAR-Lisflood</th><th>Normalised CAESAR Lisflood results</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Original CAESAR-Lisflood results - the reach displays erosional and depositional processes.</td><td>In the normalised method, there are several buffers classified as ‘stable’ (that is, with a mean change in elevation between -0.1 m and 0.1 m), which have standard deviation values ranging from 0.29 to 0.72 (illustrating a significant range around the mean values).</td></tr>
</table>

Figure C5-5 Standard deviation of areas classified as ‘stable’ but have a range of erosion and deposition processes

In contrast, the reach displayed in Figure C5-6 is generally classified as stable according to the results from CAESAR-Lisflood, with relatively few cells showing a change in elevation less than -0.1 m or greater than 0.1 m. The standard deviation of the cells in the buffer areas classified as stable are shown in the right-hand plot. The standard deviation values are lower than 0.1, indicating much less spread in the values of the cells within each buffer area.

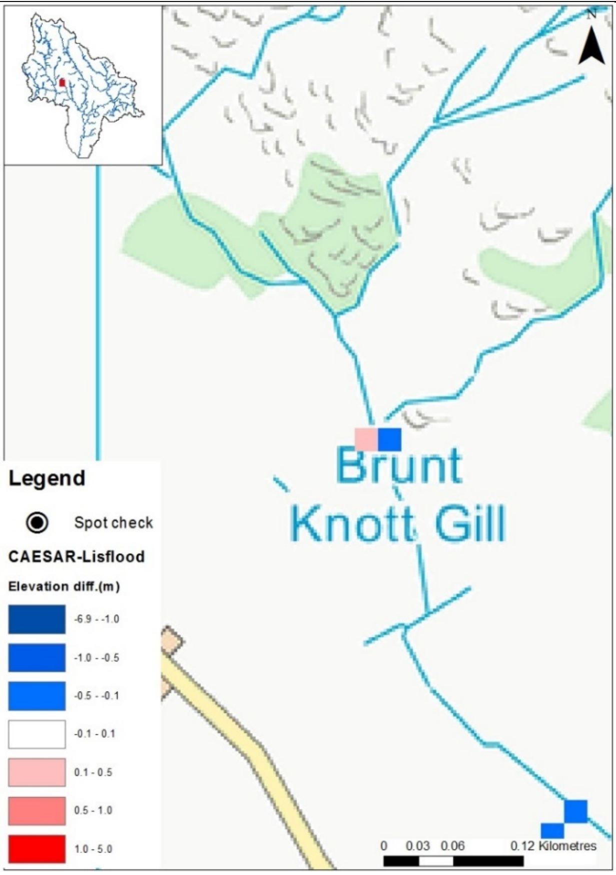
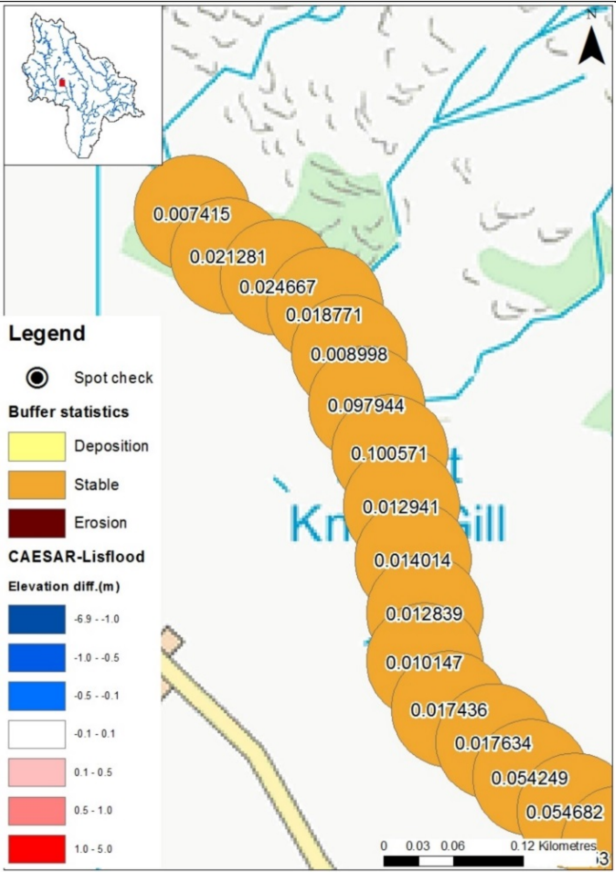
<table>
<tr><th>CAESAR-Lisflood</th><th>Normalised CAESAR Lisflood results</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Original CAESAR-Lisflood results - the reach is mainly stable, that is, with elevation difference values between -0.1 m and 0.1 m.</td><td>In the normalised method – there are several buffers classified as ‘stable’, which generally have standard deviation values less than 0.1</td></tr>
</table>

Figure C5-6 Standard deviation of areas classified as ‘stable’ but with minimal erosion and deposition processes

C5.3 Summary

This initial analysis has shown potential to normalise the outputs from CAESAR-Lisflood using a combination of the mean and standard deviation of cells within buffer regions along the channel network centreline. Further investigation of the other statistics derived from the analysis (minimum, maximum, majority) is required, since using further parameters is likely to improve the methodology. The analysis should also be extended by looking at further areas within the 3 test catchments.

For use as a national level tool, there is believed to be a potentially significant benefit in normalising the raw CAESAR-Lisflood model outputs, allowing the most dominant geomorphological processes to be highlighted while removing the complexity of the raw raster grid. It would be recommended to use the normalised data set as a high-level tool to identify key reaches that may need managing, while retaining the raw model outputs to allow a secondary, localised reach analysis to be carried out.

Appendix D: Stour and Wharfe catchment results

Due to the document size, Appendix D is provided in a separate document (FRS17183/R2 Appendix D).

D1- ST:REAM, CAESAR-Lisflood and half-yield results validation in Stour and Wharfe catchments

D2- Shear stress data mining results validation in Kent, Stour and Wharfe catchment

Appendix E: Half-yield method climate change trial

E1 Overview

This appendix details the climate change testing that was carried out for the half-yield method. The method used to adjust the baseline (current day) flows to account for climate change is described. Results are presented for the half-yield method, which was simulated with flows adjusted for climate change at the spot check locations introduced in section 5 of the main project report.

E2 Incorporating climate change into the half-yield method

Climate change can be incorporated into the half-yield method by adjusting the flow duration curves, which are intrinsic to the method. A flow duration curve is a mathematical representation of the flow regime of a river. Its shape and scale reflects the current vulnerability of the river to extreme flows. However, this may change in future due to climate change.

There is no standard UK method for adjusting flow duration curves to account for climate change. There are however a number of possible ways this could be achieved. A logical approach is to use the outputs of the Centre for Ecology and Hydrology's Future Flows project. Future Flows used rainfall run-off modelling techniques to estimate river flows under different climate scenarios based on UKCP09. The outputs are available free of charge for non-commercial use under licence agreement, and using Future Flows outputs for modelling the potential impact of climate change on river flows is an accepted method in UK water resources planning.

For this study, the Future Flows Hydrology data set has been used. This data set comprises modelled river flow time series for 282 gauged locations in the UK, spanning from 1951 to 2098. It reflects the progressive impact of climate change on river flows based on the SREAS A1B emission scenario. For any gauged locations that are relevant within the context of this project, the relevant time series will be analysed to inform flow duration curves that are representative of the impacts of climate change.

E3 Method for adjusting flow duration curves for climate change

Projections of river flow from the Future Flows project have been used to adjust the existing flow duration curves on the Kent catchment for anticipated climate change by the 2080s. Using outputs from the Met Office Regional Climate Model (HadRM3-PPE), the Future Flows project has developed a collection of 11- projected scenarios of daily river flow time series (1951 to 2098) for river flow gauging stations across Great Britain (referred to as Future Flows Hydrology). These 11 plausible scenarios (all equally likely) of nearly 150 years of river flow regime provide a means of evaluating the impact of climate change on low flow statistics.

The steps taken in adjusting the flow duration curves on the Kent catchment are as follows:

1. The Future Flows Hydrology has been used to derive flow duration curves at local gauging stations (73005, 73009 and 73011) for the present day and the 2080s.

2. For each of the 11 scenarios at a given gauging station, the 2080 flow duration curve has been divided by the present day duration curve, generating a suite of change factors.

3. For each percentage exceedance at a given gauging station, the median change factor has been calculated.

4. The median change factors, plotted below, have been used to adjust the existing flow duration curves (generated for the baseline simulations) at the ungauged subject sites (the same donor gauging stations, as adopted on the project already, have been used).

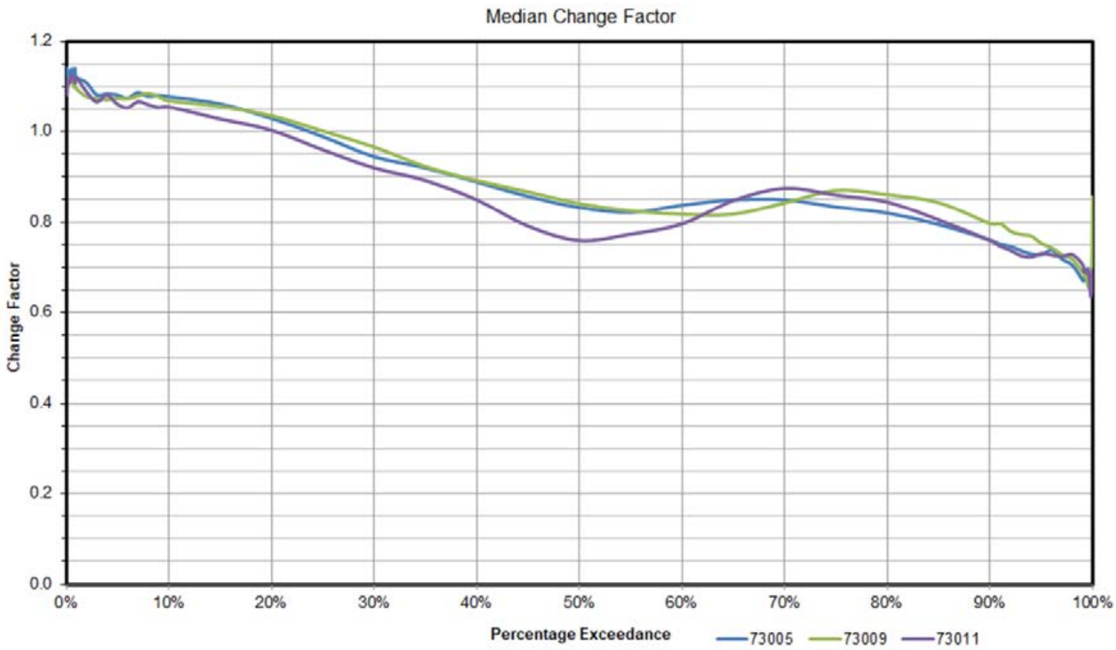


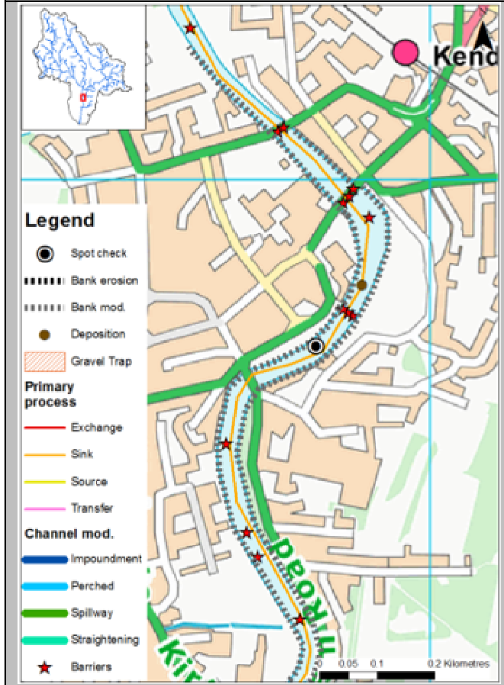
Figure E.1 Median change factors for Kent catchment gauging stations

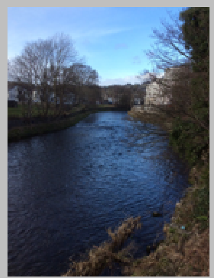
E4 Trial results

The half-yield method was rerun for the RHS data points in the Kent catchment using the flow duration curves adjusted for climate change. All the other input data was retained as per the initial Kent trials with baseline flows. The results were compared for the Kent spot check locations for which RHS data points are available (Spot check locations Kent_03, Kent_04, Kent_05, Kent_06 and Kent_09). This comparison is presented in the following figures.

Reach: Kent_03, Watercourse: River Kent, OS NGR: 351801, 492711

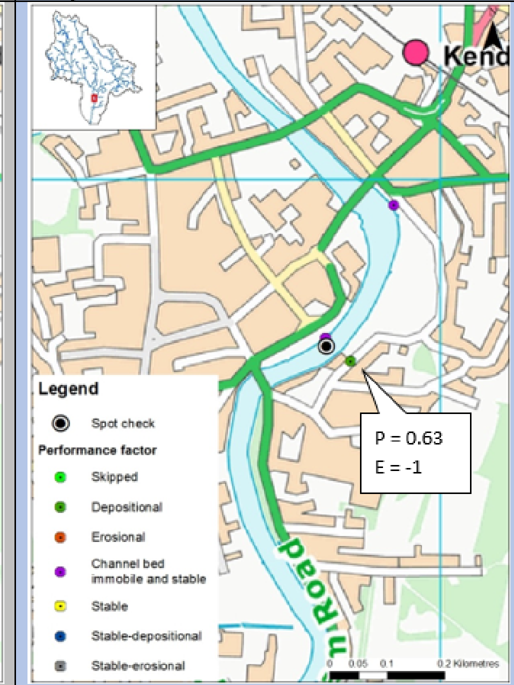
Audit data





- The channel is confined, embanked, overwide and walled with no floodplain connectivity.
- As a result of the artificial channel environment, in particular the overwide nature of the channel alongside the numerous weirs and bridges, extensive deposition across the bed occurs.
- Characterised by plane riffle morphology.
- Key process(es): Deposition

Half-yield baseline flows



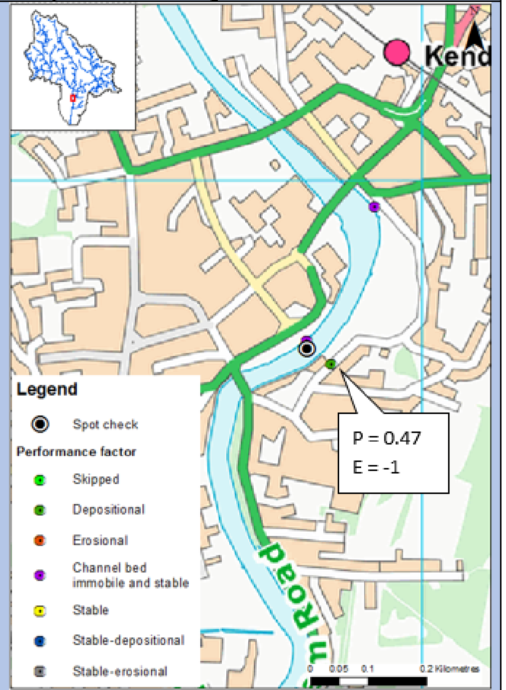
In the **Half-yield** method, there are three RHS data points within the vicinity of the spot check location.

One RHS point is classified as depositional in terms of the Performance Factor (P = 0.63) and Effectiveness Index (E = -1). This indicates:

- The channel is wide (possibly incised)
- In-channel flows dominant
- Frequent flows most effective at depositing
- Bar-berm building (possibly bed raising)

Two RHS points are calculated to have an immobile and stable channel bed. This indicates that the channel will act as a transfer reach for smaller sediment sizes and potentially depositional for fines. Channel banks might also be subject to erosion in high energy reaches.

Half-yield climate change flows



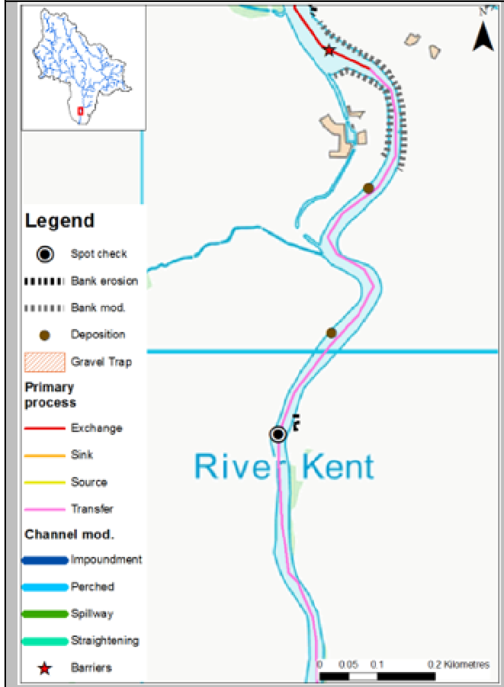
With climate change flows applied, the RHS points retain their classification, i.e. the overall predicted geomorphic behaviour does not change, with one 'depositional' and two 'channel bed immobile and stable' RHS points.

The Performance Factor of the RHS point classified as depositional drops slightly from 0.63 to 0.47. This decrease does not drop the value below the threshold value of 0.4 (which would lead to the reclassification of the RHS point into the 'Stable-depositional' class).

Figure E.2 Kent_03 – Half-yield baseline and climate change comparison

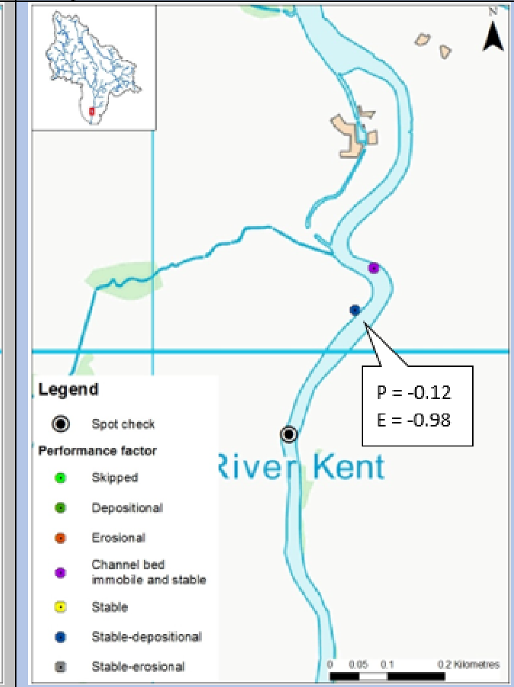
Reach: Kent_04, Watercourse: River Kent, OS NGR: 351236, 489857

Audit data



- Downstream of Kendal the channel is confined and several bedrock dominated reaches exist.
- Sediment storage in bars is limited and most is transported through the system.
- Small pockets of bank erosion and poaching.
- Key process(es): Transfer

Half-yield baseline flows



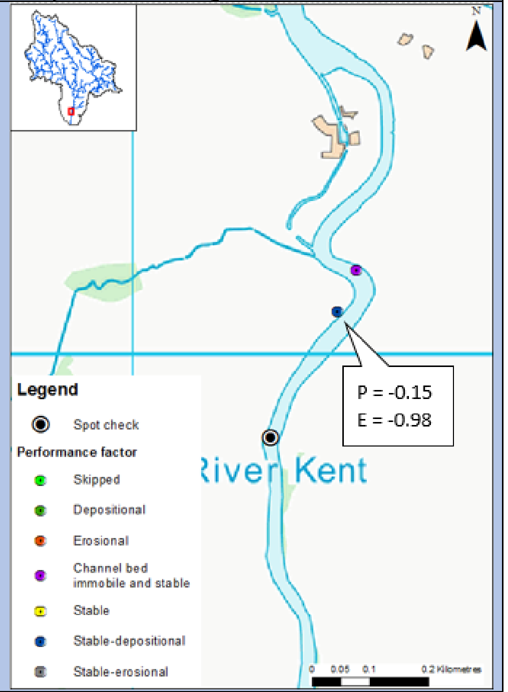
In the **Half-yield** method, there are two RHS data points within the vicinity of the spot check location.

One RHS point is classified as stable-depositional in terms of the Performance Factor (P = -0.12) and Effectiveness Index (E = -0.98). This indicates:

- In-channel flows dominant
- Incised/recovering
- Frequent flows most effective at depositing
- Gradual bed raising

The other RHS point Is calculated to have an immobile and stable channel bed. This indicates that the channel will act as a transfer reach for smaller sediment sizes and potentially depositional for fines. Channel banks might also be subject to erosion in high energy reaches.

Half-yield climate change flows



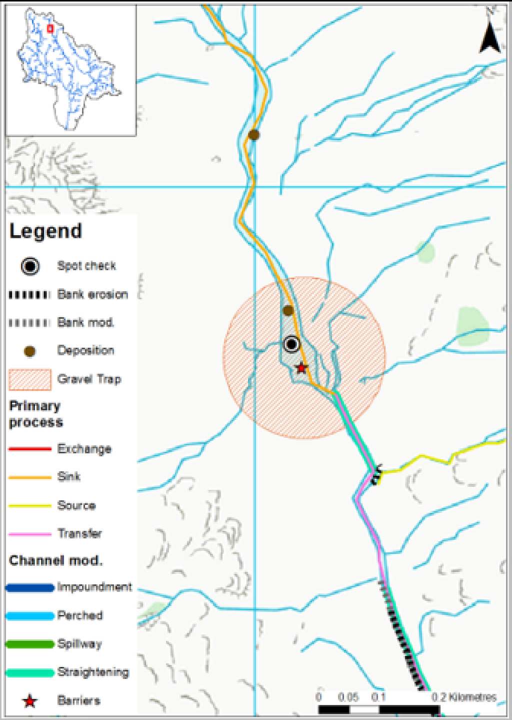
With climate change flows applied, the RHS points retain their classification, i.e. the overall predicted geomorphic behaviour does not change, with one 'Stable-depositional' RHS point and one 'channel bed immobile and stable' RHS point.

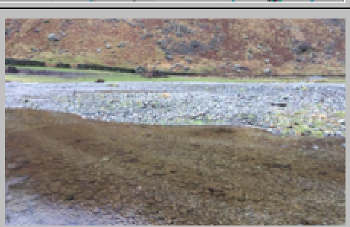
The Performance Factor of the RHS point classified as Stable-depositional drops slightly from -0.12 to -0.15. This decrease does not drop the value below the threshold value of -0.4 (which would lead to the reclassification of the RHS point into the 'Erosional' class).

Figure E.3 Kent_04 – Half-yield baseline and climate change comparison

Reach: Kent_05, Watercourse: River Sprint, OS NGR: 348060,506740

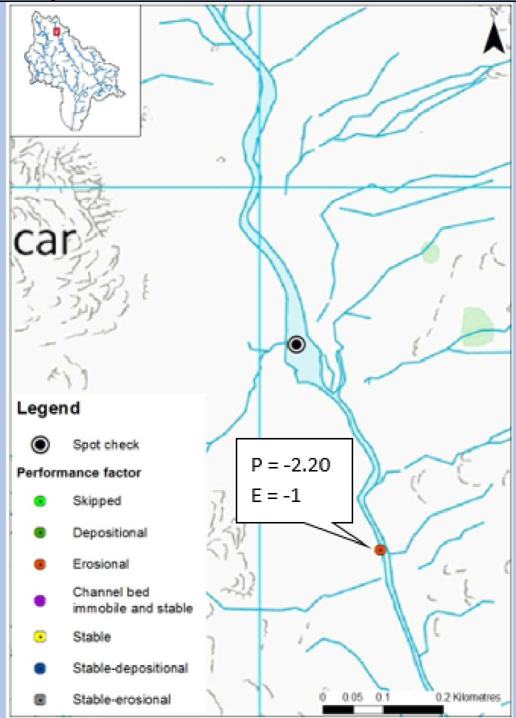
Audit data





- Former quarries upstream of spot check have left a legacy of redundant mine tailings, which act as a significant sediment source.
- Gravel trap exists as the channel gradient reduces away from initial headwaters.
- The trap is no longer maintained and is full of sediment.
- Key process(es): Deposition/transportational

Half-yield baseline flows

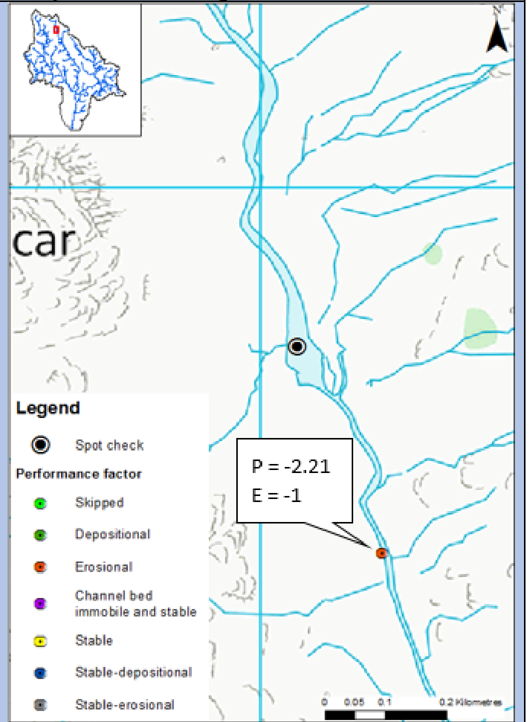


In the **Half-yield** method there is one RHS data point located downstream of the spot check location.

The RHS point is classified as erosional in terms of the Performance Factor (P = -2.2) and Effectiveness Index (E = -1). This indicates:

- Channel is narrow/incised (significant)
- In-channel flows dominant
- Frequent flows most effective at eroding
- Bank erosion

Half-yield climate change flows



With climate change flows applied, the RHS point retains its 'Erosional' classification, i.e. the overall predicted geomorphic behaviour does not change. The Performance Factor drops slightly from -2.20 to -2.21.

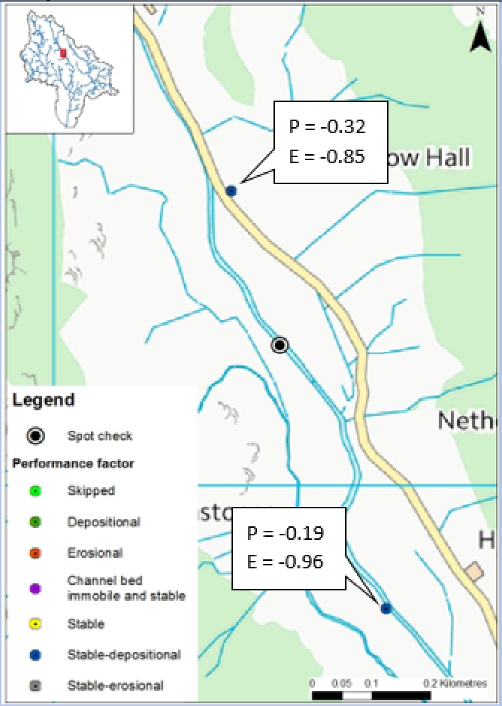
Figure E.4 Kent_05 – Half-yield baseline and climate change comparison

Reach: Kent_06, Watercourse: River Sprint, OS NGR: 350381, 502239

Audit data

- Channel has undergone historic channel management, via training walls, embankments, straightening and dredging.
- Modifications have led to elevated velocities and minimal areas of deposition, as well as minor incision and floodplain disconnectivity.
- Key process(es): Transfer

Half-yield baseline flows

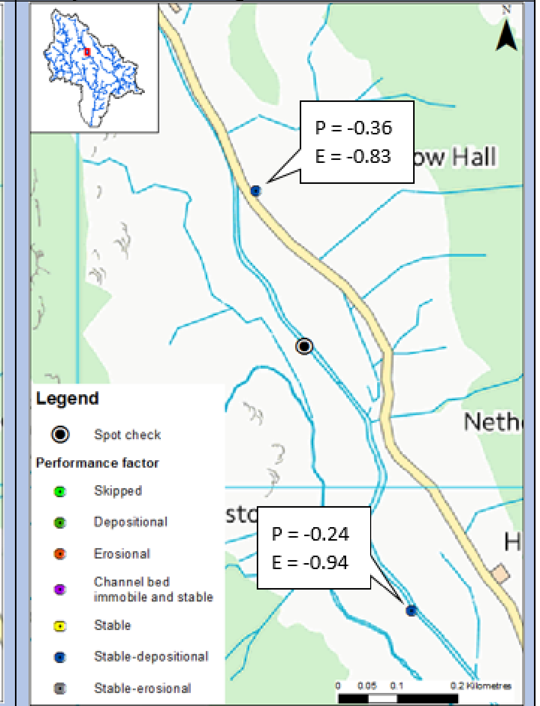


In the **Half-yield** method, there are two RHS data points within the vicinity of the spot check location.

Both RHS points are classified as stable-depositional in terms of the Performance Factor (P = -0.32 and -0.19) and Effectiveness Index (E = -0.85 and -0.96). This indicates:

- Channel is wide (possibly incised)
- In-channel flows dominant
- Frequent flows most effective at depositing
- Bar-berm building (possibly bed raising)

Half-yield climate change flows



With climate change flows applied, the RHS points retain their classification, i.e. the overall predicted geomorphic behaviour does not change, with two 'Stable-depositional' RHS points

The Performance Factor of the RHS points drops slightly from -0.12 to -0.15, although the decease is not enough to drop the value below the threshold value of -0.4 (which would lead to the reclassification of the RHS point into the 'Erosional' class).

Figure E.5 Kent_06 – Half-yield baseline and climate change comparison

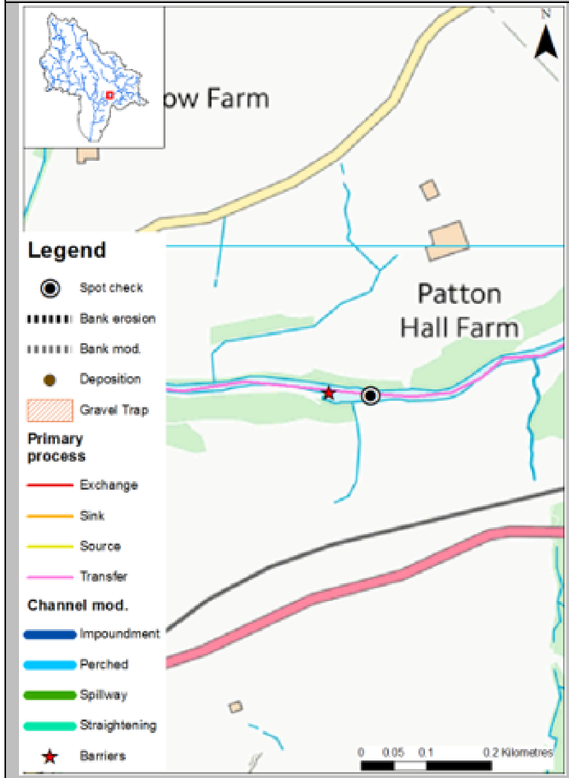
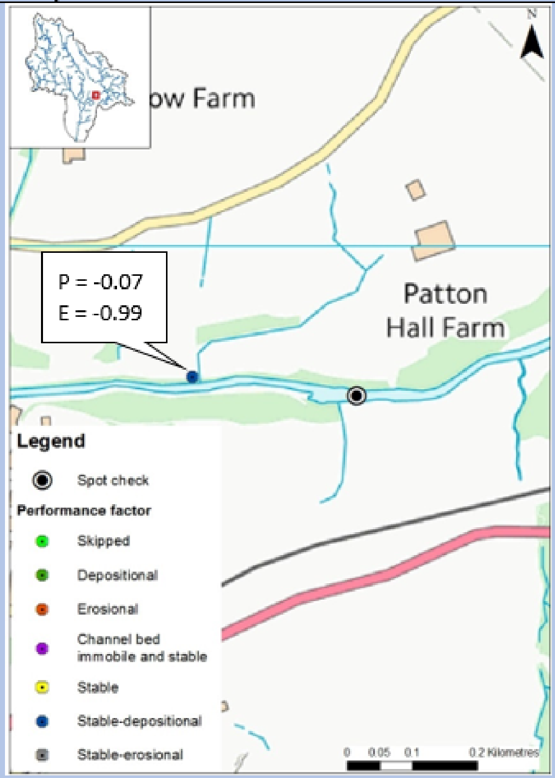
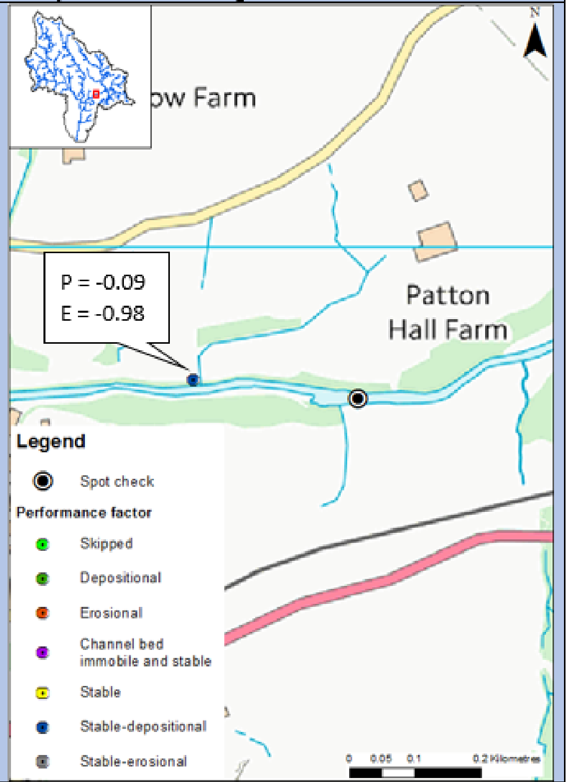
Reach: Kent_09, Watercourse: River Mint, OS NGR: 354652, 495770		
Audit data	**Half-yield baseline flows**	**Half-yield climate change flows**
		
• Channel switches from unconfined to confined floodplain areas. • Sediment deposition limited, with the exception of a few point bars where the channel gradient reduces. • Predominantly plane bed.  Key process(es): Transfer	In the **Half-yield** method there is one RHS data point within the vicinity of the spot check location. The RHS point is classified as stable-depositional in terms of the Performance Factor (P = -0.07) and Effectiveness Index (E = -0.99). This indicates: • In-channel flows dominant • Incised/recovering • Frequent flows most effective at depositing • Gradual bed raising	With climate change flows applied, the RHS point retains its 'Stable-depositional' classification, i.e. the overall predicted geomorphic behaviour does not change. The Performance Factor drops slightly from -0.07 to -0.09.

Figure E.6 Kent_09 – Half-yield baseline and climate change comparison

E5 Discussion

The half-yield results presented in Figure E.2 to Figure E.6 are summarised in Table E.1 for both baseline (present day) and climate change river flows.

Table E.1 Baseline and climate change half-yield method results (P = performance factor, E = effectiveness index). Change given in brackets.

Spot check	Baseline *P*	Climate change *P*	Baseline *E*	Climate change *E*
Kent_03	0.63	0.47 (-0.13)	-1.00	-1.00 (0)
Kent_04	-0.12	-0.15 (-0.03)	-0.98	-0.98 (0)
Kent_05	-2.20	-2.21 (-0.01)	-1.00	-1.0 (0)
Kent_06	-0.32 -0.19	-0.36 (-0.04) -0.24 (-0.05)	-0.85 -0.96	-0.83 (+0.02) -0.94 (+0.02)
Kent_09	-0.07	-0.09 (-0.02)	-0.99	-0.98 (+0.01)

Overall, adjusting the flow duration curves to account for climate change did not significantly change the half-yield results at any of the spot check locations. The performance factor decreased slightly at all spot check locations, which reflects a tendency towards increased erosional behaviour. However, the change was not significant enough to alter the classification of the any of the half-yield results. The effectiveness index either increased slightly, or did not alter, at all spot check locations. An increase in the effectiveness index reflects a change from a reach dominated by in-channel sediment processes towards one where the sediment load is more balanced between in-channel and overbank flows. However, the increases were not enough to significantly alter the half-yield method results.

The trends in the half-yield method results were similar across the Kent catchment (that is, in RHS data locations other than the spot check locations). Of the 28 RHS data points with half-yield results, all but one retained its half-yield classification, with similar trends to those described above. One RHS data point, located adjacent to the golf course between Burneside and Kendal, changed classification as a result of using flow duration flows adjusted to account for climate change. At this location, the baseline half-yield method results indicated that the reach is stable-depositional. When the half-yield method was rerun with the FDCs adjusted for climate change, the results indicated that the reach becomes erosional.

E6 Conclusion

The climate change trial has shown that there is a general trend for the half-yield method climate change simulations to reflect a tendency towards more erosional behaviour, and a channel with a sediment load balanced between in-channel and overbank flows compared to the baseline simulations. However, the change between the baseline and climate change simulation was not large enough to alter the classification of any of the half-yield results for the majority of the RHS data points.

It did not take an experienced hydrologist a long time to adjust the flow duration curves to account for climate change, using the method described above. Following some initial adjustments to the coding, rerunning the half-yield method with the climate change flow duration curves was then as straightforward as running the initial, baseline half-yield simulations.

Appendix F: Method learning points

F1 Overview

This appendix outlines the main learning points that have come out of the trial phase of the project. Specifically, the following are outlined for each method:

- recommendations for what the Environment Agency would need to consider or change if the method is rolled out nationally
- technical recommendations to improve the method setup
- technical lessons learnt
- limitations and benefits for Environment Agency use

F2 ST:REAM

F2.1 Main recommendations/considerations to help national upscaling

- For national scale modelling, it would be proposed to apply the method at a catchment scale, combining the method outputs to produce a national level data set. If this methodology was used to generate reliable method outputs at a national level, a modelling team would be needed in each catchment, each applying a consistent approach.
- The method as a whole requires expertise in GIS. National scale modelling would require an integrated team with specific expertise.
- National upscaling would be feasible. However, some hard work would be needed, including creating the correct topology/relationship of the river branches in all catchments in the UK.
- The national scale model outputs would require analysis and quality assurance at a catchment scale, increasing time requirements.
- Sensibility checks of results at a catchment scale would be required, using regional and local geomorphological knowledge.

F2.2 Technical recommendations (to improve method setup)

- For step 4 of the ST:REAM method, it was necessary to remove any channels not in the network as well as secondary channels or any branches < 1 km. At present, this is time consuming as it has to be done manually. In future, it would be beneficial to alter the way in which the processing is carried out, as outlined in the following steps:
    - For example, step 9:

      'Identify the branches to include in the model – those with a DA>= 1% of the total catchment DA (Change the symbology of the DA layer to indicate all cells containing DA >= 1% of the total DA to help with this'

- This could be applied earlier in the process at step 4 to reduce the number of features and how they are 'cleaned'. Identifying the streams with this characteristic from the DA grid earlier in the process means that the streams that have a smaller catchment could be ignored. The classified DA grid could be exported to a shapefile and used to select the features of the DRN or OpenRivers shapefile. Better still, a drainage network polyline could actually be created from the DA grid and used as the source of the branch points. If a good DTM is available that has a better resolution than the DA grid, after a few steps (step 7 or Hydrotools steps needed to create catchments) a drainage network for the required catchment size could be delineated from the DTM.
- The benefit of using a drainage network produced from the DTM flow accumulation grid is that it is almost clean. The location of the polylines will be as accurate as the DTM. While a DRN would be more accurate in terms of location, it is questionable whether this accuracy is actually needed. What are needed are points representing the centrelines that have an order, so the relationships between the points are important and not the location per se. Moreover, the other inputs are coming from different sources that are not as accurate and they are joined to the branch points by spatial joins that are spaced every 10 to 50 m, therefore exact X and Y locations are not considered to be crucial. If a really accurate network is needed, the DRN could be selected using the drainage network from the DTM, meaning that there would not be too many polylines to clean at the end of the process.

- Another small change that could potentially be useful concerns step 7 for the Catchment Model Builder. This is a python script that is supposed to be added into ArcGIS to create an Arc toolbox. The ability to do this depends on the level of expertise of the person carrying out the instructions. Since their coding specialist on this project understands Python quite well, JBA ran this as a standalone python script instead. While this approach worked well, JBA felt the annotation within the script wasn't very detailed, so it was hard to see the progress of the script. Also, if the script failed on an early step, through the toolbox there would be no way to start the script at a later point. To improve this, checkboxes could be added onto the toolbox allowing the user to select which specific steps to run.
- In project correspondence, Dr Chris Parker of the University of the West of England suggested an alternative, quicker way of generating model input data that could more easily be scaled to the national scale. He has suggested that an experienced ArcGIS programmer could create a script to carry out the following steps in a few days and this could then be run in batches for catchments across the whole country in approximately one week. Chris raised concerns about the suitability of the width and slope values from the DRN though as they will be averaged across the segment (rather than being specific to each measurement point). The outputs from using the DRN width and slope values would need to be compared to the outputs from the original source of input data to verify their suitability. The alternative method comprises the following steps:

- ‘clean’ DRN feature class to create a single thread representation of main branches in catchment network - remove small side channels (<1 km length), secondary channels
- use Terrain 5 contours and simplified DRN to generate hydrologically correct DTM
- generate DA raster from DTM
- generate modelled catchment drainage network
- create a Qmed raster grid
- create separate feature classes for each branch of the catchment
- creates measurement points along each branch
- spatial joins channel width and slope to measurements points from DRN
- extract Qmed values for each measurement point
- export values to ST:REAM model

F2.3 Technical lessons learnt

- One of the most time-consuming and unexpected hurdles to overcome for this method was encountered when combining the OS MasterMap topography layers. Due to unknown reasons, these layers at certain extents did not appear to load/display all features. Consequently, when combined, the layers seemed to have lost some of the required features. After many unsuccessful attempts to join the layers from different geodatabases in a number of different ways, it was decided to use another program ‘FME’ to combine the layers. This was successful, and it was decided to continue using this program to combine the layers for future catchments to avoid wasting further time on this. It is suspected that this is a result of a new delivery platform for MasterMap or Arc versioning. The JBA GIS specialist working on this method has significant experience working with large extents of MasterMap data over many years and has never previously encountered this issue. The MasterMap data is used to delineate channel width. According to the GIS specialist, the way in which the width is calculated is the weakest parameter of the 3 main inputs (Q2, contours and width).
- While the GIS process to calculate approach is sensible, the spreadsheet is relatively cumbersome and the coding could be improved. The GIS specialist found that the code did not always produce sensible slope estimates (which was not picked up at first) and these had to be manually checked and adjusted.

F2.4 Limitations/benefits for Environment Agency use

- ST:REAM is actually estimating the net gain and loss of sediment within a reach. However, in terms of sediment dynamics, identifying key areas of current deposition and erosion is different. This reflects the complexity of the geomorphological processes which are dependent on historic processes within a catchment or reach. The method represents a single snapshot in time and cannot tell us at what stage we are at in the channel evolutionary model. For example, in high energy, active environments (such as the River Wharfe) it is possible for the method to illustrate a net accumulation of sediment, which has accumulated over a long time period. However, the current processes are likely to be erosional, since there is a lot of alluvial sediment available to be eroded. Conversely, in reaches that have lost a lot of sediment over time, it is likely that there will be no erosion since the channel has reached bedrock.

- Varying success rate of predicting geomorphological processes has been illustrated across the 3 trial catchments, suggesting that the method is not appropriate for all river types.
- In terms of asset managers' requirements, the method cannot predict net erosion or deposition rates or lateral instabilities. However, it can highlight key network behaviours, for example, eroding reaches, which would be beneficial within asset management planning.
- Some geomorphological understanding is required when interpreting results in order to sensibility check the results. The threshold for erosion, balance and deposition reaches also needs to be established, requiring calibration to the existing catchment.
- When applied at a national scale, there will be a need to co-ordinate multiple catchment teams, potentially leading to inconsistencies between each catchment and reduced efficiencies when integrating the individual catchment model outputs.
- Trials revealed inconsistencies in method application, requiring manual checks on some of the automated processes, increasing resource/time requirements.

F3 CAESAR-Lisflood

F3.1 Main recommendations/considerations to help national upscaling

- Overall, JBA feels that modelling CAESAR-Lisflood at the national scale would be feasible, but would require access to adequate computing infrastructure (cloud computing) and a team of hydraulic modelling specialists.
- The potential to semi-automate any of the methods required in model setup or parameterisation could be an interesting research and development project, which could be worth pursuing if the approach is applied at a national scale.
- For national scale modelling, it is proposed that the method is applied at a catchment scale, combining the method outputs to produce a national level data set. In order to generate reliable method outputs at a national level, a modelling team would be needed in each catchment, each applying a consistent approach. It is recommended that a guidance document is developed, detailing each element of parameterisation and model setup, to avoid an inconsistent approach being followed in each catchment.
- The method as a whole requires expertise in hydrology, hydraulic modelling and geomorphology. National scale modelling would require an integrated team with specialist hydraulic modelling knowledge, although specific user-

training courses and someone senior overseeing the process could reduce the need for a full team of experienced modellers.

- Upscaling nationally is primarily a resource issue. The greatest time spent in any CAESAR-Lisflood application is related to the input data, especially the DEM generation. Actual model run times can be long, but require no human intervention so are relatively cost effective. Professor Coulthard of the University of Hull advises that in previous work carried out for the Environment Agency, the data sets that need to be merged to create the DEM (that is, the defences, LiDAR, hard structures) are readily available, and this becomes far easier with subsequent applications.
- At a national scale, a number of individual basin models would need to be developed, rather than a single nationwide model. The models would ideally need to be calibrated to a downstream gauge to increase confidence in the outputs. The level of detail incorporated into the model can be user-defined, which would alter the time and resource requirements.
- Based on experience gained during the testing phase of this project, a 20 m resolution model in a catchment of approximately 30 km^2 would cost around £1,400 to set up, run and calibrate. However, it is likely that this would become faster and cheaper with further experience.
- The national scale model outputs would require analysis and quality assurance at a catchment scale, increasing time requirements.
- Results would need to be checked at a catchment scale to make sure that they are sensible, using regional and local geomorphological knowledge.

F3.2 Technical recommendations (to improve method setup)

- DEM resolution: JBA tested 2 m, 10 m, 20 m and 50 m resolution DEMs. 20 m resolution was found to represent the best trade-off between run times and resolution. This still took 7 days to run the Kent catchment using 25 years of rainfall data on a standard PC. The run time reduced to approximately 2 days using a higher specification PC (WAK-GPU16, latest generation 20-thread machine with 64Gb RAM and local SSD).
    - A trade-off between the resolution of data outputs and model run times will need to be assessed if implemented at a national level.
- Bedrock layer: this was found to be an important input parameter. Simply, a bedrock layer can be defined based on a threshold of slope (that is, bedrock set 0.5 m below DEM for >45 degree slope and set 1.5 m below DEM for <45 degree slope). This layer should ideally include 'hard' objects such as weirs and other control structures, urban areas, roads and railways.
- Downstream flow calibration: Ideally each catchment needs to be truncated to a downstream flow gauge in order to allow flow calibration. Otherwise, confidence in model outputs would be extremely limited. An improvement would be to calibrate flow to multiple gauges, if there are a number of flow gauges in a catchment, each with a rating curve.
    - With experience, modellers may become confident enough to model ungauged catchments. However, this would require a detailed understanding of catchment parameters and how sensitive the models are to these. Recent research by Skinner and others (2018) has outlined the sensitivity of the model to input parameters.

- Rainfall data review: importance of reviewing rainfall data records was highlighted due to some inaccurate data.
- ‘M’ value to represent catchment run-off rates: one set value can be used, but this is likely to both over and under estimate some flow peaks throughout an entire catchment. This could be improved in the future by:
  - running a large number of simulations with different ‘m’ values and choosing the best one, based on mean flow and a correlation of peaks over threshold
  - could use spatially varying ‘m’ values, perhaps based on land use or FEH catchment descriptors
- Manning’s roughness: a default value for an entire catchment can be used, but it would be better to use spatially varying ‘n’ values, based on land use.
- Warm-up phase: An initial model run for a few years is recommended in order to allow large movements of sediment to take place, which could easily be misinterpreted.
- Grain size: up to a maximum of 9 grain sizes can be added. Future development of a national grain size database (based on Marc Naura’s methodology) could be used. Improved model outputs and additional run times would need to be weighed up to determine the importance of increasing the number of grain size series.
- Drained/managed areas that are known to have a significant impact on the movement of water within the catchment should be removed from the model. This is because CAESAR-Lisflood assumes that water moves naturally from one grid square to another, with no external influences controlling/regulating this process. Examples include areas upstream of reservoirs and land drainage sites/pumped catchments. In these situations, and if erosion and/or deposition is likely to be an issue, it may be necessary/beneficial to use a combination of the ‘catchment mode’ and ‘reach mode’ models. This would allow a more accurate representation of artificial flow patterns and the resulting erosion and deposition.

F3.3 Technical lessons learnt

- The quality of the results are highly dependent on the time spent on model setup. Considerable levels of detail could be added but this would increase resource requirements and model run times.
- Methods testing has been limited to the ‘basin’ method, modelling a full catchment. If a central or downstream area of a catchment needs to be modelled in isolation, it is possible to run the upstream catchment at a coarse resolution (for example, 50 m) and use the hydraulic and sediment outputs to feed into a reach model of the location where a higher spatial resolution is required. Data formats are designed to allow this.

F3.4 Limitations/benefits for Environment Agency use

- Potentially very useful as a management planning tool due to the detailed level of outputs, although it will be dependent on resources available for interpreting the results. There are currently limitations in areas of channel realignment, although equally this could be used to highlight potential restoration opportunities.

- The method incorporates sediment inputs from valley slopes and also includes modelling of lateral erosion processes. It gives rates of accumulation and net erosion/deposition, including lateral erosion and has the potential to illustrate geomorphological change, such as landform evolution and channel avulsion.
- Some complex data requiring licensing would be needed for the model setup (such as hourly rainfall and grain size data).
- Experienced hydraulic modellers would ideally be required, but this could be overcome through specific user-training courses, someone senior overseeing the process, and through quality assurance.
- The level of detail applied in model development is user-defined, so it can vary depending on resource or data availability.
- Modelling outputs would be fairly easy to interpret following basic training, but geomorphological knowledge would be required to fully interpret the results.
- National scale modelling could feed into many projects/areas of interest for the Environment Agency and partners/external companies seeking licences.
- Some inconsistencies in model outputs (50% success rate in the Kent catchment) highlighted the need for model quality assurance and sensibility checks of the results using local geomorphological knowledge.
- The method would be resource and time intensive when applied at a national scale, and the co-ordination of multiple modelling teams across the country (developing each individual catchment model) could result in inconsistencies between the modelling approach (for example, if different DTM resolutions are used).
- Climate change can be incorporated into the model simulations and this has been previously tested in the River Swale catchment.

F4 Half-yield method

F4.1 Main recommendations/considerations to help national upscaling

- For national scale modelling, it is proposed that the method is applied at a catchment scale, combining the method outputs to produce a national level data set. If this methodology was used to generate reliable method outputs at a national level, a modelling team would be needed in each catchment, each applying a consistent approach.
- A number of manual processes required in the model setup could be semi-automated to reduce time requirements when compiling national scale data sets.
- The method as a whole requires expertise in coding, GIS, hydrology and geomorphology. National scale modelling would require an integrated team with specialist knowledge.
- Since the success rate of predicting geomorphological processes appears to largely depend on the RHS survey coverage, a primary recommendation

is to investigate the availability of an alternative data set (that is, a record of channel geometry data with greater coverage at a national scale).

- For batch processing (running multiple catchments at the same time), a virtual (unused) machine would be needed as the script accesses Excel when operating, meaning potential disruption to the user. The script opens and closes Excel documents several times and therefore if other work is being carried out in Excel, it will be closed. Accidental edits to the documents being used will cause the code to break, so this needs to be avoided.
- The national scale model outputs would require analysis and quality assurance at a catchment scale, increasing time requirements.
- Results would need to be checked at a catchment scale to make sure that they are sensible, using regional and local geomorphological knowledge.

F4.2 Technical recommendations (to improve method setup)

- Since some inaccuracies have been found in the RHS data, it would be recommended to check river widths by, for example, measuring the river width from LiDAR, aerial imagery or LiDAR.
- Due to the timescales, the Python code has been written to work around the Method Excel document that Dr Philip Soar has provided.
  - In future work, the method script could be converted into Python to streamline the code. This would reduce the running time as the computer running the code would not have to keep opening and closing programs, instead it would be possible for it to do everything in memory.
- The script uses a command line interface, which is easy to use but it would be beneficial to include a full interactive user interface allowing users to browse to locations, rather than just copying and pasting links in.
- Time constraints have also meant that it has not been possible to implement a full logging system. At present, the script writes out any cross sections that have been skipped due to null values. However, once the window closes, there is no record of this.
  - In future work, the script would benefit from adding a log, which would write out a copy of records that have been skipped. This could also allow skipped records to be separated, modified and rerun, if possible.
- The FDC ratios were created in Excel manually. This could be coded in future to make the process more efficient.
- At present the method outputs a CSV file. In order to plot the data in ArcGIS, shapefiles for the data need to be manually created from the CSVs. This process could be automated to reduce resource requirements.

F4.3 Technical lessons learnt

- Multiple limitations of using the RHS data have been identified, including:
  - some questionable river widths

- a number of RHS points had to be 'skipped' as the RHS or DRN was missing data
- a number of RHS points have been surveyed more than once, at different times. Some of the river parameters are observed to differ between years, that is different bank heights and bed sediment categories. This may be due to changes in the river system. However, it is more likely that the differences are a result of operator bias/error. It highlights the importance of the quality of the underlying data.

- The greatest hurdle with this method has been creating the contributing area catchments (the catchment areas draining to each RHS survey point).

F4.4 Limitations/benefits for Environment Agency use

- The method uses readily available data sets.
- Initial observations of the results have shown that the quality of the underlying data is key. RHS data was found to have many limitations, with some questionable river widths, some missing data and some contradictory results for the same survey location.
- At present, the code requires 4 separate input files per catchment. This is a positive feature when looking to implement on a national scale as there are no shared files. This means that it would be possible to run multiple catchments at any one time, allowing multi-batch processing.
- The model would be applied where RHS data is available, which will result in incomplete coverage if applied nationally. In addition, while data are generated for individual cross sections, the approach does not simulate spatial linkages in sediment movement between reaches.
- In areas with available data the tool could potentially be useful in highlighting key geomorphological processes and a probable method of channel adjustment. However, lack of data is a key limitation for using this as a management planning tool nationally.
- Method does not permit accounting for net erosion or deposition rate which is what asset managers need. Lateral instability is also not accounted for. It can give details of key processes at point locations, however it depends on data being available.
- Without geomorphological expertise, there is potential danger of misinterpretation. As well as initial visual assessment of GIS outputs the performance factor and the effectiveness index need to be reviewed to determine dominant geomorphological processes.
- GIS expertise would be required for some aspects of model setup (for example, catchment delineation for creating the flow duration curve).
- The method could potentially provide locally detailed data based on at-a-site efficiency, although accuracy of results depends on reliability and availability of RHS data points.
- When applied on a national scale, multiple catchment teams will need to be coordinated, potentially leading to inconsistencies between each catchment and reduced efficiencies when integrating the individual catchment model outputs.

- There are 2 methodologies for incorporating climate change into the method (by manipulating the flow duration curves).

F5 Shear stress data mining method

F5.1 Main recommendations/considerations to help national upscaling

- Since the current model simulations use a single assumption on D50 sediment size, Manning's roughness and Shield's constant, it would be recommended to develop a scenario library of outputs in a geodatabase using a range of different parameters. This would allow users to select the most appropriate local conditions. Since the model run time is approximately 12 hours, it is not expected to take long to build up a library of multiple scenarios based on different grain size distributions.
- By combining method outputs with additional catchment data, the results are shown to become more meaningful. Additional layers are therefore recommended to be incorporated into the model geodatabase to allow comparison. These should include:
    - the slowly permeable soil layer from the Working with Natural Processes project SC150005 that highlights the presence of glacial till where there is no existing tree cover
    - The Woodland_OpenMap layer in the OSOpenMapLocal_Vector data (Ordnance Survey, Open data) and the National Forestry Inventory (Forest Research, open data)
    - RHS outputs (Environment Agency, open data)
    - emerging data sets on grain size distributions
- The national scale model outputs would require analysis and quality assurance at a catchment scale, increasing time requirements.
- Results would need to be checked at a catchment scale to make sure that they are sensible, using regional and local geomorphological knowledge.

F5.2 Technical recommendations (to improve method setup)

- Modification of the shear stress data mining predictions using the presence of existing woodland. Woodland is shown to have reduced erosion and promoted stability, so it may be possible to remove some of the areas predicted to potentially be at high risk of erosion by cropping out areas of woodland from the mapping analysis. The National Forest Inventory and OS Woodland_OpenMap layers could be used to do this.
- The detailed analysis reveals that there are locations where applying a 'majority filtering', whereby rapid spatial variations are filtered out by changing isolated pixels to suit the values of the majority of neighbouring cells, would remove some of the areas of observed bank erosion and potentially reduce the level of agreement between the shear stress data mining method and audit. Small groups of pixels or single pixels may look odd, but this should only be interpreted as whether or not the shear stress meets a certain threshold. Areas of shear close to this threshold (controlled

by the Shield's constant and other variables) will oscillate around that threshold between erosion, transition and deposition.

- For large channels at the bottom of the Kent and Wharfe, the 100-year return period (1% AEP) flood tends to give better agreement than the 30-year return period (3.33% AEP) maps, so it is proposed that the 1% AEP event is used throughout. Further research on different D50 assumptions or variable D50 and the 1,000-year return period (AEP 0.1%) is recommended. Time and resources are likely to be better spent building up a scenario library and combining this with local knowledge on sediment size to determine appropriate D50 values.

F5.3 Technical lessons learnt

- Viewing the shear stress data mining outputs alone does not necessarily provide a useful picture of geomorphological change. However, combined with other data such as the valley slope, the presence of glacial till (representing an erodible sediment source) and woodland, the context and likely patterns of change are useful.
- Less data was available for the River Stour, and here the shear stress data mining method assumes a D50 that is most likely too large, so erosion is likely to be underestimated. The proposed scenario library based on different D50 values and other parameters would remove this issue, but the shear stress data mining outputs are not available for a more relevant scenario as yet. The comparisons suggest some sort of filtering of high erosion areas in riparian woodland will be necessary.

F5.4 Limitations/benefits for Environment Agency use

- Method uses a modelling approach which is well established and approved, using readily available data sets.
- Potentially very useful as a management planning tool due to the detailed level of outputs, although further investigation into results interpretation is required, such as majority filtering and a decision support framework.
- Method does not account for net erosion or deposition rate, which is what asset managers need. However, it could indicate potential areas for channel migration. The outputs could potentially provide detail on key processes (for example, potential for erosion and deposition), but this depends on further investigation and results interpretation.
- Production of a GIS layer requires limited interpretation to display key geomorphological processes, although some limitations identified in methods testing show the need for further investigation into the display of model outputs (for example, majority filtering and removing woodland).
- The outputs are visually simple yet detailed locally (2 m resolution).
- The shear stress data mining method results in outputs that make sense at a small scale (2 m) when comparing with bank erosion, a reach scale when comparing with information on average properties of a reach (available on the Wharfe), and at the valley scale when overlain with other data such as glacial till and valley slope. For example, areas of high shear stress and slopes on till-diamicton (without trees) highlight erosion and, combined with areas of low shear stress and gradients downstream, help describe a

valley-scale erosion-deposition process. The method therefore has the potential to perform well at a range of scales.

- A relatively low level of expertise is needed to apply the method. However, some geomorphology knowledge would be required to set the correct depositional threshold for different catchments (for example, to represent the most appropriate geomorphological processes/conditions such as bed armouring).
- The shear stress data mining method is easy to run nationally, with a single run possible overnight, so it would not take long to build up a library of multiple scenarios based on different grain size distributions. Combined with better local knowledge or a national grain size distribution map, the approach could be tailored and, for example, rasters of D50 or Manning's roughness values could be used (rather than a fixed value) in the Model Builder code.
- Since one national model is available, there will be no need to coordinate multiple catchment teams, avoiding the risk of inconsistencies occurring between each catchment. The method is therefore expected to be highly consistent across the UK.
- The data mining method cannot fully account for climate change since the model is applied at the national scale, preventing regional forecast uplift factors being applied. However, by comparing the 1% AEP (1 in 100-year) and 0.1% AEP (1 in 1,000-year) flood event outputs, it is possible to assess the sensitivity of modelling predictions to increases in rainfall.

Appendix G: Workshop results

A user workshop was held in May 2019 to better understand how the Environment Agency would use national data that shows the location of hotspots, where river channels are susceptible to erosion and deposition. The workshop provided:

- a valuable insight into what types of river channel change data are used now and how this is used
- feedback on how data showing hotspots where rivers are susceptible to erosion/deposition could be used, for what and by whom
- user requirements of this data and how it should be developed

G1 The current picture

Feedback from the group highlighted that many teams across the Environment Agency currently use a range of channel change data sets at both a strategic/national level as well as at a local/reach scale. Data is used for 'business as usual' as well as during/after incidents. Examples of these uses are shown in Figure G.1 and Figure G.2 below, but this is not an exhaustive list. Other users include:

- partnership and strategic overview teams that carry out in-house modelling to assess specific sites/schemes and collect topographical survey
- hydrometry and telemetry teams that need to understand channel change to choose safe and stable gauge sites post flood event
- regulation permitting, to inform response and help with abstraction permits
- environment programme teams, in terms of assessing sediment related issues with reservoirs and Water Framework Directive related restoration and improvement projects

A key theme was the lack of nationally integrated data exchange, storage and access concerning channel change and sediment management. There is a lack, for example, of a national record of what sediment management is happening and where. The discussion also highlighted that knowledge on channel changes is often provided by local experts on an ad hoc basis. Although there is some guidance/data on where gravel management is happening, the data is often not shared or stored centrally. As a consequence, historic records are not accessible due to the lack of a national survey archive. External users also need to use channel change data sets. For example, lead local flood authorities (LLFAs) need to broadly understand the potential for geomorphological changes and risk.

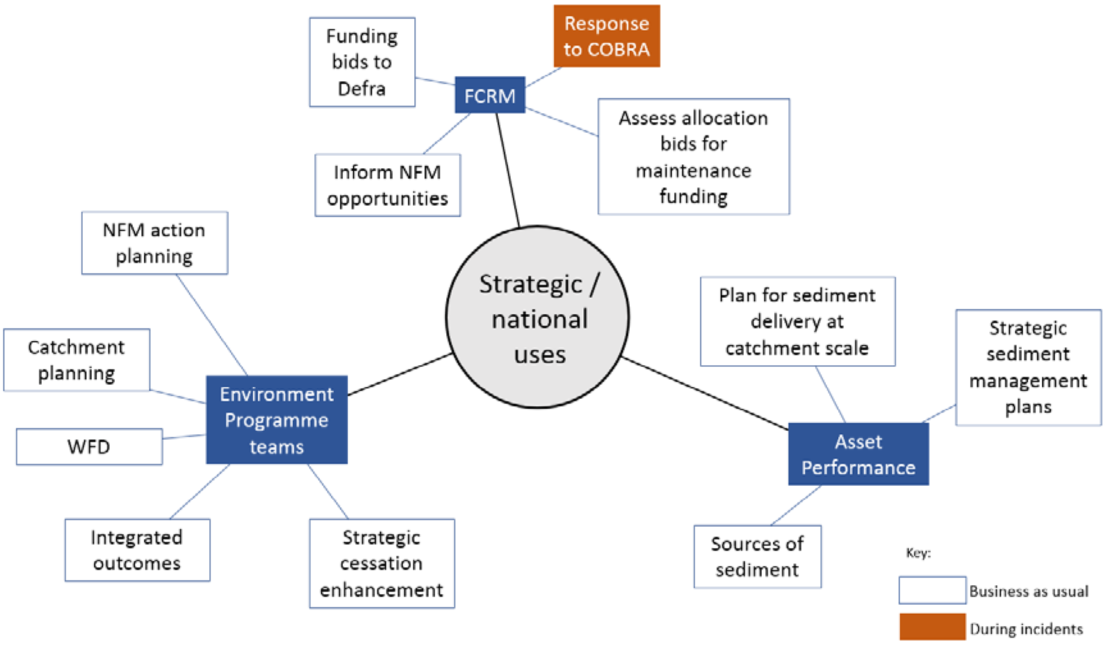


Figure G.1 Current strategic/national use of channel change data across the Environment Agency

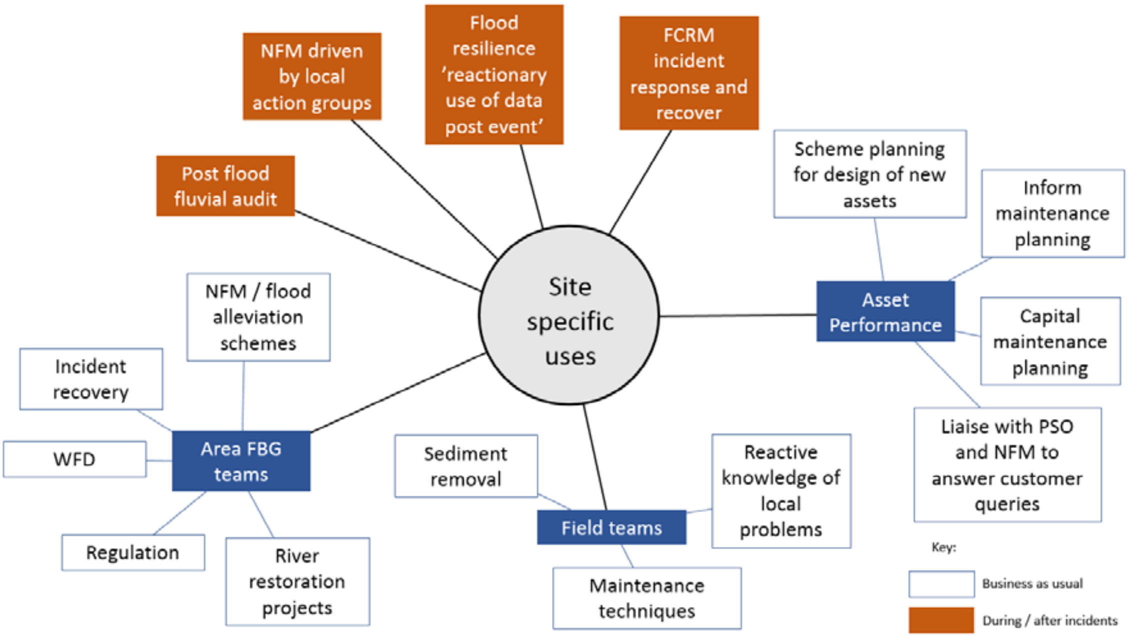


Figure G.2 Current site-specific use of channel change data across the Environment Agency

G2 Who could use data from this project and for what purpose?

Using this data can feed into many of the Environment Agency's workflows. These are presented in Table 6-1 below. This information has been provided from the experience of an Environment Agency area geomorphologist and therefore is approached from the Environment Agency's perspective.

As highlighted in the previous section, there would also be uses external to the Environment Agency, for example, the lead local flood authorities who are responsible for most of the river network covering ordinary watercourses. It is intended that this data set would be open source for everyone to use. In terms of potential uses of the data, there are currently no agreed activities. All the potential uses identified in Table G.1 would need to be investigated further.

Table G.1 Environment Agency potential uses and users of project outputs

Use	User	Notes
Inform routine and intermittent maintenance programme	Asset Performance (AP)	Hotspot mapping of erosion and deposition (provided by the method outputs) will help plan river maintenance to highlight the most critical zones. For example, where the potential for deposition/erosion is shown to be highest, needing more frequent maintenance. The outputs will help AP plan workload, programme and enter early discussion with internal teams, such as Fisheries, Biodiversity and Geomorphology (FBG) and external interested groups to make sure work is carried out in an environmentally sensitive way and at a suitable time of year.
Identifying areas where climate change may affect flood risk by erosion and deposition	AP, area Flood Coastal Risk Management (FCRM) and Fisheries, Biodiversity and Geomorphology teams, as well as external users	Outputs from the climate change method scenarios will mean changes in erosion/deposition hotspots can be identified. These can then be applied within local hydraulic models to assess any impact on flood risk. Data: maps of river reaches and function (erosion, transport and deposition).
To underpin work to develop a new benchmark metric of river morphological condition by 2020	National and area Water, Land and Biodiversity (WLB) teams, Environmental Permitting (EP) teams and FCRM teams	Key geomorphological processes will be provided at a national scale, providing critical information to steer the development of morphological condition mapping. Support WLB Head of Business Strategy and support Defra 25-year Environment Plan. Data: maps of river reaches and function (erosion, transport and deposition). Underpinning metrics (for example, stream power, sediment transport capacity).
Feed into/inform a catchment scale restoration strategy by 2020	National and area WLB teams and FCRM teams	Mapping erosion and deposition hotspots on a national scale will be a critical source of information to inform where river restoration projects should be applied. The national scale data may need to be applied within local hydraulic models in order to provide more local detail of appropriate restoration schemes at a catchment scale. CAESAR-Lisflood may prove particularly useful for this application since it often identifies historic channel routes through the flood plain, highlighting paleochannels. Support WLB Head of Business Strategy and support Defra 25-year Environment Plan. Data: maps of river reaches and function (erosion, transport and deposition).
To develop a river restoration opportunity map	National and area WLB teams, EP teams and FCRM teams	Mapping erosion and deposition hotspots on a national scale will be a critical source of information to inform where river restoration projects should be applied.

Use	User	Notes
		Support WLB Head of Business Strategy and support Defra 25-year Environment Plan. Data: maps of river reaches and function (erosion, transport and deposition).
To improve the method by which natural processes and catchment scale thinking feed into restoration planning and approach to regulating activities in and around water bodies	National and area WLB teams, EP teams and FCRM teams	Support WLB Head of Business Strategy and support Defra 25-year Environment Plan. Data: source/deposition zones on land from the data mining shear stress approach.
To inform land management advice and regulation	Agriculture, Fisheries and the Natural Environment (AFNE) and agriculture teams, Defra	Project outputs could be used to steer advice and regulation of land management practices, for example, where land management is shown to be making erosion or deposition worse. This is likely to require a more local scale assessment, following the national scale hotspot mapping.
Inform flood recovery response	Area FCRM including AP, Field Teams and Flood Resilience teams	Project outputs, if used with some expert judgement, may help Area Teams focus flood recovery activity and inform short notice funding bids in the days following large flood events.
Inform flood models and flood risk mapping	Partnership and Strategic Overview (PSO) and M&F teams	Project outputs could be shared with those involved in maintaining and updating models – a useful cross check to make sure modelling incorporates the range of potential channel changes and reflects the flood extents on that basis.
Identify where sediment accumulation increases (or doesn't increase) flood risk to property	AP, Field Teams, PSO teams, FBG teams, local flood groups	The Environment Agency is often under pressure to remove gravel from rivers; a) because it has always done this, and b) due to a perceived link to flood risk. Lack of evidence to demonstrate otherwise means teams often have to take a precautionary approach – even if this is likely to be less sustainable and more costly than other approaches. Ideally, Area teams would like to have more detailed information in terms of how gravel deposition impacts channel conveyance and flood risk. This could involve establishing known thresholds (with visual markers on site) below which gravel accumulation is not increasing flood risk. This would require site-specific modelling.
Identify or confirm 'problem sites' where physical restoration could be applied for more sustainable FCRM	AP, FBG teams	If a reach is known to be depositional and there are concerns that flood risk is increased as a result of that deposition, are there ways that this could be managed other than regular dredging/gravel management? Mapping erosion and deposition hotspots at a national scale will be a critical source of information to inform where river restoration projects should be applied. The national scale data may need to be

Use	User	Notes
		applied within local hydraulic models in order to provide more local detail of appropriate restoration schemes at a catchment scale. CAESAR-Lisflood may prove particularly useful for this application since it often identifies historic channel routes through the flood plain, highlighting paleochannels.
Informing gravel management at a multi-reach scale	AP, FBG teams	Linked to above, management interventions need to consider the bigger picture. For example, is ongoing gravel removal of sediment from a problem site depriving the downstream reaches of material leading to channel incision/impacts of fish spawning habitats?
FCRM capital plans, strategies and schemes, environmental projects	National Capital Programme Management Service (NCPMS), National Environmental Assessment Service (NEAS) and Environment Agency consultants, Environment Programme team	Project outputs would be a great starting point for scheme optioneering and to inform survey and modelling effort (resulting in cost savings). It could also provide a head start for WFD/environmental projects (such as weir removals or NFM).
Water resources WFD investigations for sediment management downstream from reservoirs	IEP	Water companies need to assess whether their activities (impounding water in reservoirs) are preventing the downstream water bodies from achieving WFD objectives. High level information provided by the project may inform this work by highlighting areas where sediment could be 'seeded' downstream of their assets to best effect.

G3 Next steps

Developing the method outputs to make sure that they are as useful as possible so users can improve their business processes is an important next step. The suggestions from the user workshop are in Table G.2 and Table G.3, summarised below. Of those listed, developing risk categories or information showing the impact of change, and having good guidance on how to use the data are considered to be the most important. Table G.2 identifies which specific scenarios can be modelled and which input/output data sets can be incorporated within the 4 methods that have been tested. Table G.3 details the remaining factors that need considering before taking forward the national scale modelling.

It would not be possible to accommodate some of these suggestions in all of the trial methods. For example, rates/volumes and quantities of sediment transported are needed for many studies. However, these would be calculated in local models rather than in an initial screening tool. Two combined approaches would work well in this case, with a simpler, national scale model such as ST:REAM or the shear stress data mining method as an initial screening tool, together with the development of a local model, such as CAESAR-Lisflood to provide more local level detail.

Of the methods the user group examined at the meeting, ST:REAM was the preferred method, followed by the shear stress data mining method. It was considered to be a good high-level tool that fits within the scale of work. There is also less need for local quality assurance testing due to the broad scale modelling outputs, although this is always recommended in key areas. In this sense, there were some concerns raised about the high resolution outputs produced by the shear stress data mining method and CAESAR-Lisflood and publishing local scale data due to a high level of detail. This would require local quality assurance which would be time consuming and resource intensive. In comparison, most of the group were comfortable with presenting the outputs of ST:REAM at a strategic level, with further detail being added using local knowledge.

Table G.2 Specific scenarios and inputs/outputs that can be achieved within the methods

	Variable	ST:REAM	Half-yield	CAESAR-Lisflood	Data mining
1. Scenarios	Long-term annual average	X	✓ (potentially if using a long-term data set in flow duration curve)	✓	X
	Short-term flood event	✓ (Qmed only)	X	✓	X
	Normal and extreme flows	X	✓ (flows represented in flow duration curve – not extreme flows)	✓	✓
2. Inputs/ outputs	Size of sediment or gravel (within model and what can be moved)	X	✓	✓	✓
	Link to out-of-channel sources of sediment	X	X	✓	X
	Rates of erosion and deposition	X	X	✓	X
	Quantity of material removed (artificially) each year and the impacts of this	X	X	✓	X

Table G.3 Remaining factors that need considering before taking forward national scale modelling

Improvement	Detail
1. Impact/risk of change	- Risk categories (for example, high, medium, low) - Greater difference in the outputs, for example, more than 2 options, although binary results could help more with strategic/early use - Help to screen the highest risk locations - Change in flood risk - Risk at gauging stations/primary forecast sites
2. Confidence/uncertainty	- Confidence limits - Sensitivity tests (for example, how sensitive are outputs to any input changes?)
3. Local factors	- Geology - Risk receptors - Potential to add more factors where available/when needed (adaptable content) - Existing gravel management locations need to be considered - Impact on permitting
4. Guidance	- What positive things the data can be used for (for example, opportunities for restoration or to reduce maintenance costs) - Summary sheets to explain data and its uses (short document, FAQs) - Guidance on how physical change equates to flood risk (or not), to help public discussion - Clear statement describing what the maps/data is for (for example, in plain English) - Relevant warnings made clear - Clear description of what the data shows and how it should be interpreted and used
5. Local quality assurance	- Need a way to ground truth or quality assure with local knowledge, with a feedback loop to update product. This has resourcing implications – it may be that data should only undergo quality assurance where it is really needed

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