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Understanding river channel sensitivity to geomorphological changes

Creating pilot data sets showing potential for erosion across England and Wales using the shear stress data mining method

FRS17183/R4

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

Research approach

This study is documented in 4 reports:

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

Various methods have been tested and evaluated to assess the ability to predict in-channel geomorphological activity at the reach scale, under both existing conditions and with future climate change (FRS17183/R2).

One of these methods is called the shear stress data mining (SSDM) method, developed by JBA Consulting.

This report provides a summary of the SSDM method and its assumptions, and outlines the research carried out to select the modelled scenarios. The model code, simulations and geo-spatial outputs are described for the scenario library maps showing potential for erosion and the climate change testing.

Method

The SSDM method uses the large, nationally consistent, high resolution depth and velocity data from the models used to produce the Environment Agency's risk of flooding from surface water (RoFSW) maps, to estimate the shear stresses created by the frictional force per unit area of water running over the river bed, and uses these to estimate the potential for erosion. To do this, the SSDM model uses Shields relationship (Komar,1988) with an estimate of the grain size of bed material to define the critical shear stress. Above this critical shear stress, local bed material is expected to mobilise (move).

This was used to define zones where erosion would be expected in river channels and across the flood plain where flow routes were present in the RoFSW maps.

Main findings

This research 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. A scenario-library of maps was developed to encompass a range of values of the grain size distribution and the closely related Manning's 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 maps can be interpreted in the same way as the RoFSW map to define areas of 'very low, low, moderate and high' risk of erosion.

Further calculations were made to highlight erosion sensitivity to climate change at the broader scale (5 km). Here, a proxy for the expected 40% increase in rainfall intensity until 2080 has been used based on the climate impacts tool (Environment Agency, 2019)[1], by way of the increase in the predicted areas of erosion across the 25 km^2 tiles that formed the model domains in the RoFSW maps. The increase in total rainfall between the 3.33% and 1% annual exceedence probability (AEP) represents an uplift in the range 32.3% to 44.7% and is similar in size to the projected changes in the Environment Agency climate impacts tool for 2080 (40%). The difference between the area with potential for erosion for these probabilities for a given scenario reflects the expected changes with a 40% uplift in rainfall intensity.

Across 10 scenarios, the average increase in potential for erosion is 526 km^2, representing 0.33% of the modelled area of England and Wales. Assuming an average channel width of 5 m, this equals an average expected increase in erodible channel length of 100,000 km by 2080, compared with the present day. These figures represent a large increase in the potential for erosion due to global heating, which will have a knock-on effect on channel maintenance activities, land-use change and water quality.

The SSDM method was tested against survey information in 3 catchments of the Kent, Wharfe and Stour in England (FRS17183/R2 Appendix D), where it was shown to predict areas of likely erosion and deposition. The report further relies on physical reasoning and research, demonstrating that evaluating shear-stressed 2D model outputs can be informative with regards to measured geomorphic change (Reid and others, 2018). However, there is a great deal of uncertainty (for example, drainage pathways can be misrepresented) where the RoFSW map is less accurate due to the underlying topographic definition, especially for areas that were not covered by the more accurate LiDAR data in the composite digital terrain model (DTM) from 2012. Where LiDAR data was not available in 2012, the spatial data should therefore be used to help identify areas where greater caution will be needed in using the outputs from this study. The method would also benefit from mapping of distributed grain size distribution, which is not yet available as a national data set.

Next steps

Additional work is needed to understand how these maps would be used in operational activity for flood risk and environment management. However, having a scenario library of maps showing potential for erosion with varying grain sizes and annual exceedance probabilities, the appropriate scenario can be selected based on the user need and local parameters for grain size and channel roughness.

[1] UKCP18 is broadly consistent with UKCP09. This version of the climate tool therefore continues to be valid for risk screening, representing the best available information and illustrating a useful picture of potential future challenges.

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1 Introduction

1.1 Scope and context

Various methods have been tested and evaluated to assess the ability to predict in-channel geomorphological activity at the reach scale, under both existing conditions and with future climate change. This is described in research report FRS17183/R2. One of these methods is called the shear stress data mining (SSDM) method and was developed by JBA Consulting (JBA).

This report describes the work to develop a pilot national data set for England and Wales, showing the potential for erosion using the SSDM method.

A select number of scenarios have been developed within 3 months to demonstrate the value of providing maps that show potential for erosion and deposition across England and Wales.

This report describes:

- the method
- how the scenarios were selected
- the model simulations
- model outputs
- the model limitations
- future recommendations

2 Shear stress data mining method

2.1 Data used in the SSDM method

The shear stress data mining (SSDM) method uses existing large-scale, high resolution model data to create the risk of flooding from surface water (RoFSW) maps (Environment Agency, 2012). This includes a 2 metre resolution depth and velocity information covering England and Wales for a range of probability events (0.1%, 1% and 3.33% annual exceedance probability (AEP).

2.1.1 Data sets used in the SSDM method

The following national data sets have been used:

- National DTM: Integrated height model 2 m resolution digital terrain model (Environment Agency, licensed data). This topography was used to drive the surface water flood inundation modelling, and has been used in this project to understand depths and velocities.
- Risk of flooding from surface water (RoFSW) complex model outputs (Environment Agency, open data), continuous rasters of depths and velocities. These are maximum mosaics across the national 5 km tiles and across 3 storm durations (1, 3, and 6 hours), for each of 3 annual exceedance probabilities (3.33%, 1%, and 0.1% AEPs). The depths and velocities have been used to extract shear stresses, the basic frictional force exerted by water flowing over the bed material.
- The RoFSW data set includes the rainfall totals used for each probability event. These were used to assess the difference in rainfall totals between probability events to help compare with the predicted change expected due to climate change.
- 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. This was used to understand land cover near high shear stresses when comparing the shear stress distributions derived in this study.
- The slowly permeable soils layer from the open data mapping outputs of the Working with Natural Processes project (Hankin and others, 2018). This is based on the British Geological Survey (BGS) superficial geology 'till-diamicton' layer, but with areas of woodland removed. It is used here to indicate sources of erodible material.

2.1.2 Risk of Flooding from Surface Water maps

The Risk of Flooding from Surface Water (RoFSW) maps were produced using a direct rainfall with 'Revitalised Flood Hydrograph (ReFH) losses' approach, whereby net rainfall was estimated in relation to local hydrology, and a 2D flood inundation model, JFlow ® (Lamb and others, 2009) was used to route the resulting flows over a 2 m resolution raster DTM. The outputs were improved with feedback from the lead local flood authorities (LLFAs) across England and Wales in 2012.

The peak depths and velocities were computed through the rainfall event. The accuracy of the depths and velocities greatly depends on the accuracy of the 2 metre DTM and the representation of the channels and flow accumulation pathways within the DTM.

The DTM (produced in 2012) comprised:

- 2 m resolution LiDAR. The root-mean squared error (RMSE) is 0.15 m in the vertical) where available, mainly in urban areas on large rivers in 2012
- 5 m Nextmap Britain SAR data resampled to 2 m resolution everywhere else. The RMSE can be as large as 1.0 m in vertical

Relatively short duration (1, 3, and 6 hour) summer storm profiles were used over 5 km tiled domains (25 km^2 rainfall grid), and then mosaiced together for each probability to produce the RoFSW probability maps. In 2012, Environment Agency and LLFAs were consulted to validate and, where possible, support with refined local data.

The short durations imply 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' of rainfall on the terrain and surface drainage system.

2.2 Using the RoFSW model to calculate shear stress

2.2.1 Background

This research 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.

Similar approaches such as re-using 2D modelling outputs, with validation against field data (Reid and others, 2018), and using physics-based formulations of erosion potential (Lane and others, 2005) have been used for some time. Reid and others (2018) showed that a shear stress based approach derived from 2D model outputs helped to understand gravel bar evolution when combined and compared with very high resolution terrestrial LiDAR.

The SSDM method uses an efficient ESRI ArcGIS model builder code to calculate local shear stress based on average velocity and depth (from the RoFSW model) and roughness. It takes approximately 12 hours to apply the method across rivers in England and Wales.

This research project has applied the SSDM method efficiently to create a pilot scenario-library based on a range of assumptions. This could allow users to select an appropriate scenario depending on their local conditions.

2.2.2 Overview of the method

The SSDM method uses the hydraulic data sets from the RoFSW model together with estimates of channel roughness to derive shear stresses at a 2 metre resolution. The

Shields relationship (Komar,1988) was used together with an estimate of typical grain size of bed material in order to define the critical shear stress. Above this critical shear stress, the forces acting per unit area on the local bed material are expected to mobilise. This was used to define zones where erosion would be expected in river channels and across the flood plain where flow routes were present in the RoFSW maps. A deposition factor was introduced to define zones where deposition is expected, assuming that at 30% of the critical shear. The zone between erosion and deposition is known here as ‘transition’. This is where smaller grain sizes may also mobilise, or larger sediments may be settling.

Overall, this produces a zonal classification of sediment erosion, transition and deposition, which can be calculated for a range of assumptions, although much of the focus here is on the zones of erosion.

A toolbox was generated to assess climate change sensitivity at the larger scale (25 km^2) based on changes to the erodibility between different probability events (assuming likely impacts of climate change on rainfall intensity). This is further explained in section 6.

2.2.3 Calculating bed shear stress

For a steady flow of water over a river bed, there is a balance between the gravitational force and the frictional resistance exerted by the material on the bed. The frictional resistance per unit area represents a shear stress, which if large enough can mobilise the bed material. This is termed the critical shear stress, which is specific to the density and grain size of the bed material.

Effective shear stress can be derived from the following quadratic expression, which gives the correct dimensional construct for shear in relation to depth and the square of the depth-averaged velocity (Lane and Ferguson, 2005, Bates and others, 2010):

$$\tau_0 = \rho g \frac{n^2}{d^{1/3}} v^2$$

Where τ_0 is effective shear stress (N/m^2), ρ is density of water (kg/m^3), g is acceleration due to gravity (m/s^2), n is the Manning’s coefficient ($s/m^{1/3}$), d is depth (m) and v is depth averaged velocity (m/s).

This relationship can be compared against critical shear stress for the average grain size of material expected to be present to identify where erosion is more likely. It is important to note that the expression is based on depth averaged velocity, and approximates the shear stresses resulting from complex turbulent flow over typically variable bedforms in meandering channels.

2.2.4 Method parameters

The method uses a number of parameters including:

- Manning’s roughness, which is used to lump together the energy losses due to frictional resistance. This widely used coefficient is unfortunately dimensional ($s/m^{1/3}$), so depends on depth and velocity, although it is often modelled as being constant
- the D50, which is the median grain size, for which half the bed material is smaller
- the Shields constant, which is an empirical coefficient based on observation

- deposition factor is a fraction applied to the critical shear stress, below which most material present will not be mobile. It should be remembered that the critical shear stress relationship is based on the median grain size, so smaller material present can be mobile. The deposition factor helps us distinguish between zones where most material will remain on the bed for a given flow, but it again approximates over a range of factors at work, such as natural armouring of the bed, making mobilisation less likely for a given grain size

The relationships have been encoded in ArcGIS Model Builder (Figure 2.1), although this can be adapted (or translated, for example, to Python) and has been used experimentally on smaller catchments to understand the potential for hydromorphic change (see Hankin and others, 2019).

This formulation was originally developed by Kate Bradbrook of JBA, but has been adapted in this research project. For instance, some of the fixed variables have been changed to raster data sets to experiment with variable D50 grain size and Manning's roughness values.

It has also been simplified to only produce raster outputs, since the vector outputs are very large and can have storage implications.

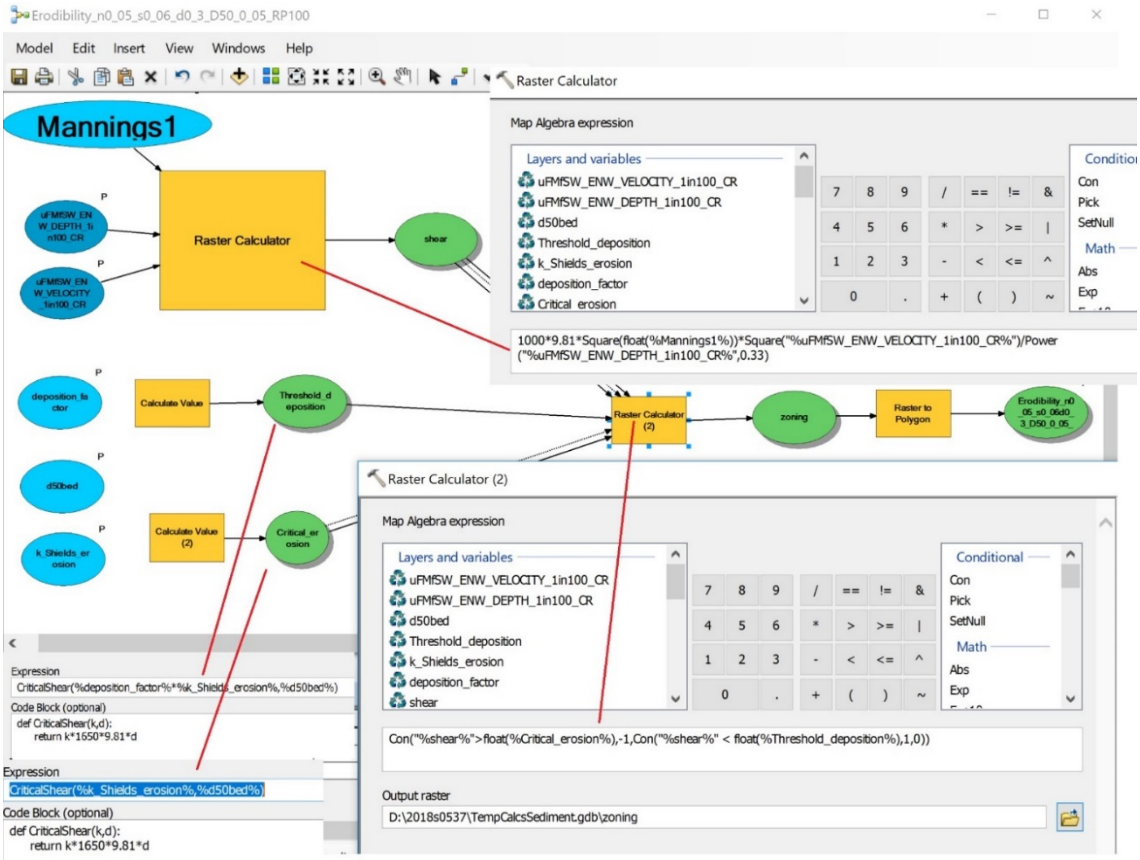

Figure 2.1 Shear stress data mining model builder with interpretation

3 Scenario selection

3.1 Overview

A number of appropriate scenarios has been selected to combine different Manning's roughness, D50 (median grain size) and Shield's constant parameters. New research has been carried out into the empirical relationships between Manning's roughness and D50.

3.2 Selecting D50 values (grain size)

The SSDM method uses D50 values to represent grain size in the river bed. This is used to determine how mobile the sediment may be on average, and therefore how likely it is to be susceptible to erosion.

Grain sizes ranging from coarse sands to small cobbles (2 to 80 mm) have been selected to cover a high proportion of channel substrate types within England and Wales, but not including finer silts and clays. Table 3.1 details the 7 D50 grain sizes selected for testing. At smaller grain sizes (0.2 mm), the threshold stresses for particle entrainment needs to increase as they are submerged in the laminar sub-layer, and not subject to the greater stresses experienced in the turbulent flow (Knighton, 1998)

Table 3.1 Chosen D50 values for testing

D50 (m)	D50 (mm)	Grain size
0.08	80	Cobble
0.06	60	Coarse pebble
0.05	50	Pebble
0.025	25	Pebble
0.01	10	Gravel
0.005	5	Fine gravel
0.002	2	Coarse sand

3.3 Selecting Manning’s roughness appropriate to grain size

Research into the empirical relationships between Manning's roughness and D50 values has been carried out to assess appropriate values to use in the model scenarios.

Milhous (2015) provides a summary of 3 appropriate equations for calculating Manning's roughness using values of D50. These include the Strickler equation [Eq. 1], least absolute deviation (LAD) relation [Eq. 2] and 20% quantile equation [Eq. 3], all of which can be used for hydraulically rough beds.

Equation 1 Strickler equation

$$n = 0.0132(D50)^{1/6}$$

Equation 2 Least absolute deviation

$$n = 0.0087(D50)^{0.5}$$

Equation 3 20% quantile equation

$$n = 0.0077(D50)^{0.43}$$

The above equations and the central D50 values selected (Table 3.1) have been used to span a range of appropriate Manning's roughness values for each grain size within the various scenarios (Table 3.2). Given the time available, only 10 grain-size-roughness combinations were used together with the average Shields value of 0.045. Given the limited number of scenarios, a range of D50 and Manning’s n were covered as highlighted in blue in Table 3.2.

Table 3.2 Calculated Manning’s roughness (n) using selected D50 values

Grain Size		Manning's n estimates		
D50 (m)	**D50 (mm)**	**Max**	**Middle**	**Min**
0.08	**80**	0.176	0.078	0.051
0.06	**60**	0.132	0.067	0.045
0.05	**50**	0.11	0.062	0.041
0.025	**25**	0.055	0.044	0.031
0.01	**10**	0.028	0.022	0.021
0.005	**5**	0.019	0.015	0.011
0.002	**2**	0.012	0.01	0.004

3.4 Shield’s constant

Komar (1988) suggests that a value of 0.045 is a good approximation for a hydraulically rough bed, common condition in natural streams, and this is supported, for example, in Knighton (1998).

The models will represent grain sizes of coarse sands to cobbles, so a value of 0.045 for all scenarios is deemed most appropriate.

Lower Shield's constant values are suggested for channels with grain sizes of approximately 0.3 to 0.7 mm. However, the lowest D50 tested here is 2 mm, so this would not be appropriate.

3.5 Deposition factor

A deposition factor of 0.3 was selected for all scenarios to help distinguish between zones of erosion and deposition. Zones of erosion are estimated based on the physics of mobilisation at a critical shear stress for the median grain size. Small particles are likely to be mobilised at lower shear stresses, so deposition actually refers to non-mobilisation. It is the zones of erosion that are more important in this mapping exercise.

3.6 Final scenario matrix

A representative 10 scenarios have been chosen to pilot in the model simulations. These were each simulated for the 3 annual exceedance probabilities for rainfall of 3.33%, 1% and 0.1%. The 10 scenarios are presented in Table 3.3.

Table 3.3 Scenario matrix of Manning's roughness (n), D50, and Shield's constant

Scenario	Selected parameters	Grain size description
1	D50 = 0.08 m	Cobble
	N = 0.050	
	Shield's = 0.045	
	Deposition factor = 0.3	
2	D50 = 0.06 m	Coarse pebble
	N = 0.050	
	Shield's = 0.045	
	Deposition factor = 0.3	
3	D50 = 0.050 m	Coarse pebble
	N = 0.05	
	Shield's = 0.045	
	Deposition factor = 0.3	
4	D50 = 0.050 m	Coarse pebble
	N = 0.07	
	Shield's = 0.045	
	Deposition factor = 0.3	
5	D50 = 0.025 m	Small pebble
	N = 0.05	
	Shield's = 0.045	
	Deposition factor = 0.3	
6	D50 = 0.025 m	Small pebble
	N = 0.035	
	Shield's = 0.045	
	Deposition factor = 0.3	
7	D50 = 0.01 m	Gravel
	N = 0.05	
	Shield's = 0.045	

Scenario	Selected parameters	Grain size description
	Deposition factor = 0.3	
8	D50 = 0.01 m	Gravel
	N = 0.03	
	Shield's = 0.045	
	Deposition factor = 0.3	
9	D50 = 0.005 m	Fine gravel
	N = 0.02	
	Shield's = 0.045	
	Deposition factor = 0.3	
10	D50 = 0.002 m	Coarse sand
	N = 0.015	
	Shield's = 0.045	
	Deposition factor = 0.3	

3.7 Model simulations

The SSDM Model Builder code (Figure 2.1) was run for all 10 scenarios presented in Table 3.3 for the 3 AEPs for rainfall of 3.33%, 1% and 0.1%.

The results are stored in a single ArcGIS 10.4 file geodatabase, which uses systematic naming convention shown in Figure 3.1. The 30 scenarios (3 probabilities * 10 bed-types) are stored as rasters within a file geodatabase, the names of which have 6 parts:

S1_ …Code for grain size/roughness scenario

RP100 …Return period. RP100 is the 100-year return period or 1% AEP

n0_05 …Mannings n is 0.05

s0_045 …Shield’s constant 0.045

d0_3 …Deposition factor 0.3

D50_0_08 …D50 grain size 0.08 m

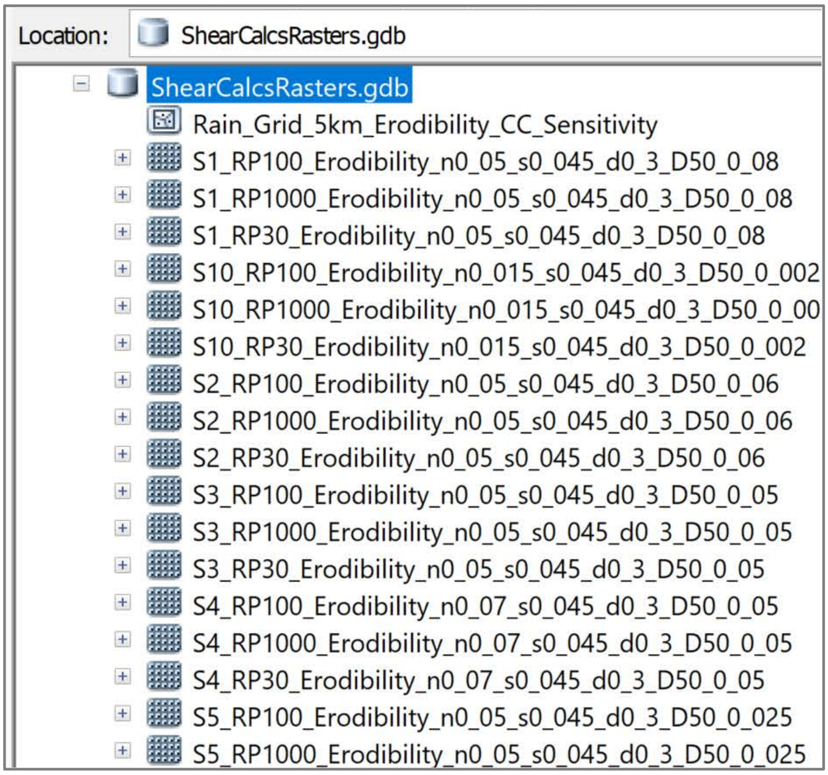

Figure 3.1 Metadata for the new scenarios showing systematic naming

The model builder Toolbox is also provided with each of the scenarios. This has explicit instructions to help rerun the scenarios with new data and for quality control. The naming convention for the Toolboxes is the same as for the rasters above, and shown in Figure 3.2.

Figure 3.2 Sediment analysis toolbox with 30 modules for each scenario simulated

The metadata for the ESRI file geodatabase is included with an accompanying spreadsheet.

4 Scenario results

4.1 Model outputs

Figure 4-1 shows typical outputs above Braithwaite, Cumbria for a large sediment size (D50 = 0.08 m, n = 0.05) for the 100-year return period or 1% AEP SSDM output. There was considerable erosion and works upstream of this village during Storm Desmond in 2015.

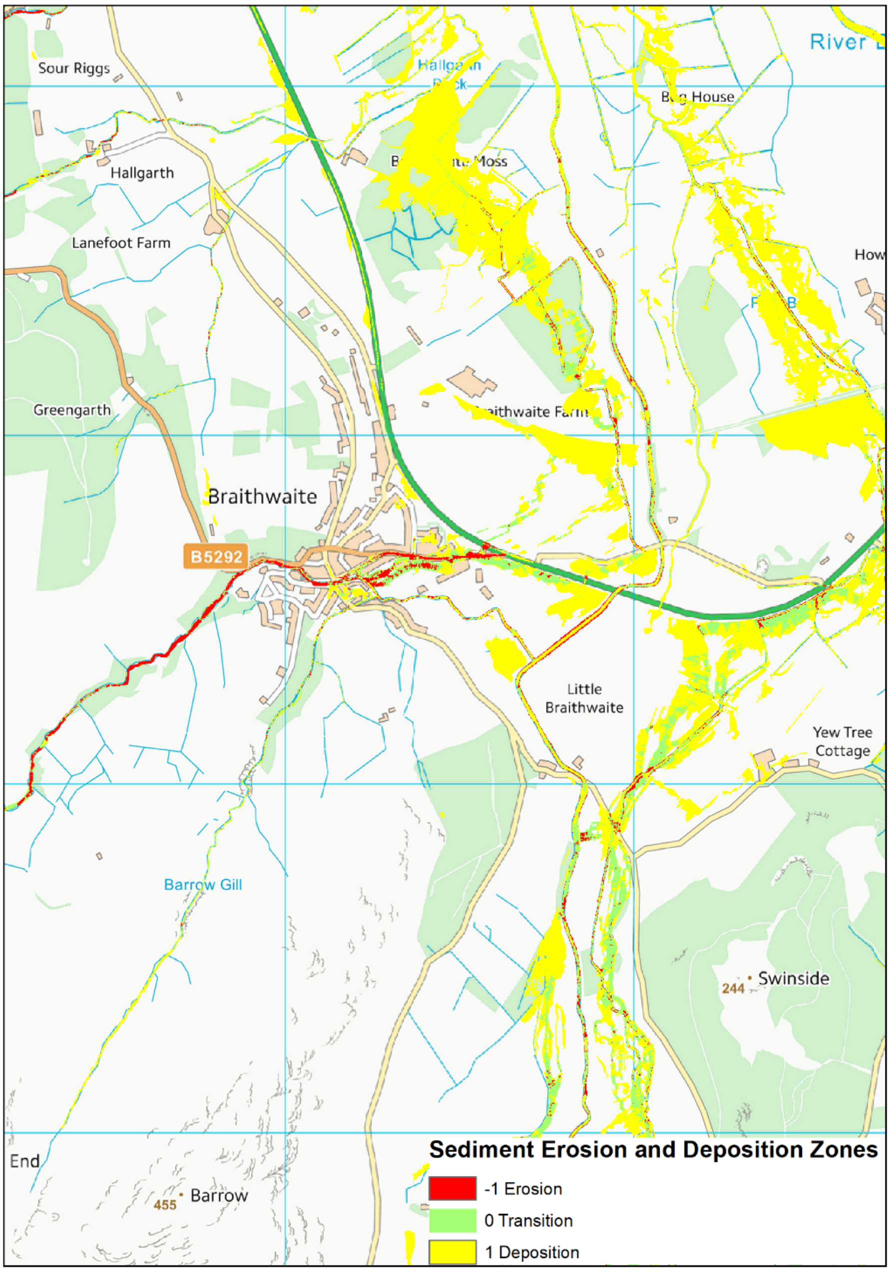

Figure 4.1 Outputs of SSDM showing zones of erosion in red

By estimating different zones of erosion or deposition for different probability flooding, it is noted that subsequent maps of erodibility can be interpreted in a similar way to the RoFSW maps. That is to say the zones for the different probabilities can be classed as 'low, medium or high probability of erosion', as per Figure 4-2.

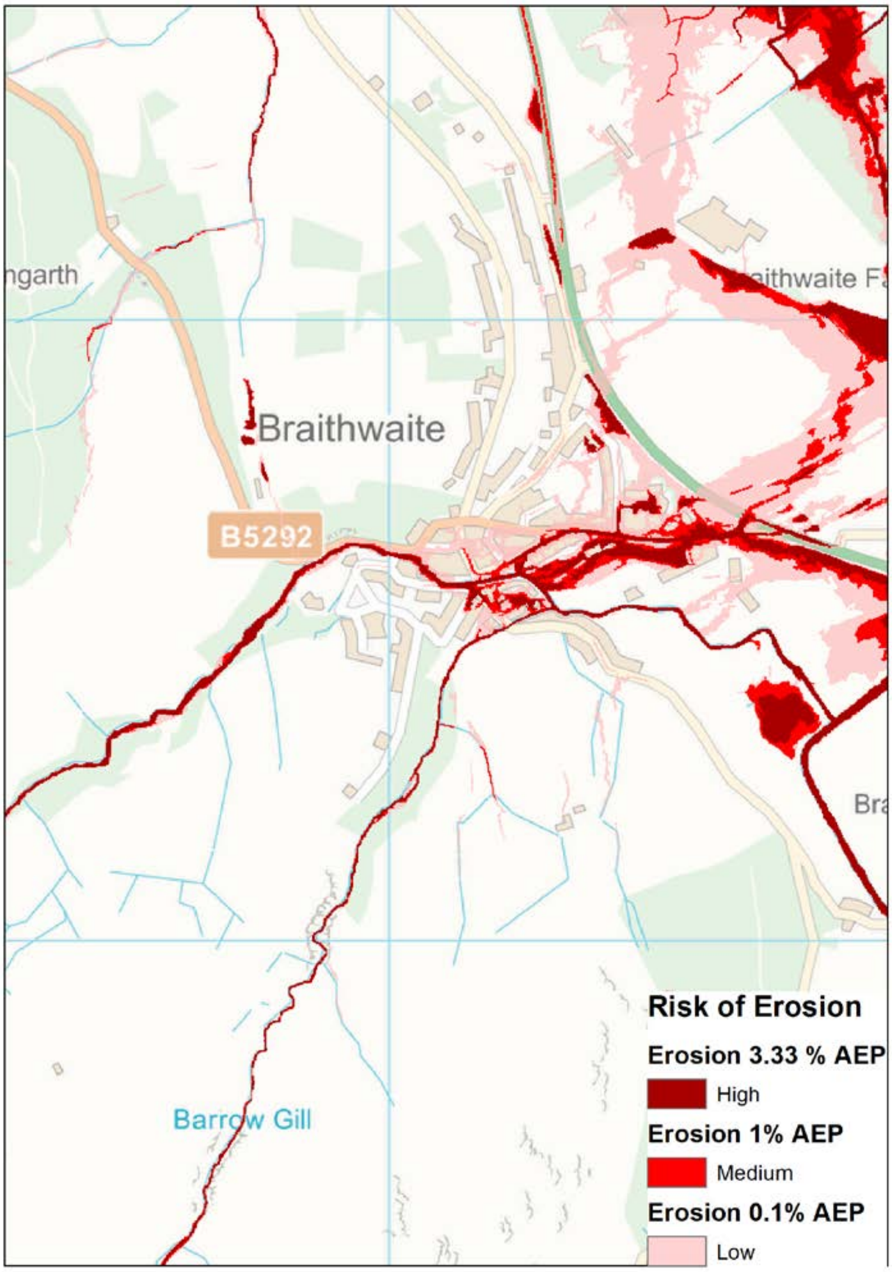

Figure 4.2 Risk of erosion map for scenario 1: n = 0.05; D50 = 0.08 m

However, it is difficult to summarise the outputs from the SSDM across the country, since there are 30 grids at 2 m resolution. Figure 4.3 provides some statistical analysis of the 10 scenarios, with further analysis in section 6 on climate change.

Scenario	D50 (m)	Manning's n	RP30 - Erosive Area (% area England and Wales)	RP100 - Erosive Area (% area England and Wales)
S1	0.08	0.05	0.10%	0.23%
S2	0.06	0.05	0.15%	0.35%
S3	0.05	0.05	0.19%	0.43%
S4	0.05	0.07	0.37%	0.77%
S5	0.025	0.05	0.37%	0.78%
S6	0.025	0.035	0.19%	0.42%
S7	0.01	0.05	0.64%	1.25%
S8	0.01	0.03	0.34%	0.73%
S9	0.005	0.02	0.31%	0.67%
S10	0.002	0.015	0.40%	0.84%

Figure 4.3 Summary of erosive area using SSDM

In this figure, the influence of Manning’s n and grain size can be seen. While the D50 decreases from scenario 1 to 10, the Manning’s roughness has been varied to give a bigger range of combinations. The combination with the largest erosive area is scenario 7, with a relatively large roughness and small D50.

5 Model verification, discussion and limitations

5.1 Model verification

Fluvial audits were provided for the River Kent and River Wharfe to carry out model spot checks. The audits centred on bank erosion, rather than in-channel scour, so the spot checks focused on whether the national model predicts processes seen in the field at the bank edges. Key ‘sediment sinks’ are also recorded in the fluvial audit data sets, representing areas of deposition. For the River Wharfe, additional data on particular reaches was available, including 'significant erosion' or ‘deposition’ areas.

The checks assumed that D50 = 50 mm in the available SSDM maps is most representative of the River Wharfe and River Kent, and is likely to be too large for the River Stour. The fluvial audit process aims to identify a range of types of geomorphological form and features within a reach, rather than solely identifying broader-scale processes. Therefore, further validation would be needed if the maps were to be used for operational processes.

The spot checks carried out in the Kent, Wharfe and Stour are presented in FRS17183/R2 Appendix D.

For most of the spot checks, the 1% AEP (100-year return period) event was used and found to most closely align with the audit observations. This becomes more important further downstream, where the 3.33% AEP (30-year return period) does not predict significant shears stresses where bank erosion is present in the fluvial audit. While the 0.1% AEP event might provide better agreement further downstream of large systems, it is likely that the variability of D50 may account for this. A number of scenarios reflecting differing D50 results would allow users to select appropriate D50 values using local knowledge of sediment size.

To further validate the scenario library results, the zones of erosion, transition and deposition were compared between scenarios and probabilities.

Two model reviewers checked the 30 scenario outputs at a selection of random locations across England and Wales. This was to make sure that there was increasing erosion with increasing roughness, but an inverse relationship with grain size (smaller grain sizes requiring a lower critical grain size before mobilisation).

The results at a number of spot-check locations were compared against the following:

- 3.33%, 1% and 0.1% AEP results
- varying D50 (grain size) values, where the remaining parameters are the same
- varying Manning’s values, where the remaining parameters are the same

The differences between the scenarios were checked to make physical sense, such as the erodible areas for small grain sizes should be larger than for large grain sizes (as a coarser bed is more resistant to erosion), and the areas of erosion should be typically greater for the higher rainfall probabilities. Conversely for zones of deposition, these should decrease in size with larger floods but increase as the grain size becomes larger. When comparing the results for differing Manning’s roughness values, lowering the roughness value was shown to consistently correspond with reduced erosion.

5.2 Discussion

Looking in detail at the results in the 3 test catchments (FRS17183/R1 Appendix D) helped identify a range of possible improvements:

- Viewing SSDM outputs alone does not necessarily provide a useful picture of geomorphological change. However, combined with other data such as the valley slope and the presence of glacial till (an erodible source of sediment) and woodland, the context and likely patterns of change are useful. Section 5.2.1 explores this concept further.
- Modification of the SSDM 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 be at high risk of erosion (for example, see Figure 2-10) by cropping out areas of woodland. Forest Inventory and OS 'Open Woods' layers could be used to do this. Section 5.2.2 explores this.
- The detailed analysis reveals that there are locations where applying a 'majority filtering' (lots of variations in one small space are filtered out by changing pixels to suit the values of the majority of the neighbouring cells) would remove some of the areas of bank erosion. This could potentially mean that the SSDM results and audit may not agree as well. 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 Shields constant and other variables) will oscillate around that threshold between erosion, transition and deposition. The approach is explored in section 5.2.3.
- Less data was available for the River Stour, and here the SSDM assumes a D50 that is most likely too large, so erosion is likely to be underestimated. The scenario library based on different D50 values and other parameters may remove this issue. The comparisons suggest some sort of filtering of high erosion areas in riparian woodland will be necessary.
- For large channels at the bottom of the Kent and Wharfe, the results for the 100-year return period (1% AEP) flood represents the audits better than the 30-year return period (3.33% AEP) maps.

5.2.1 Presence of glacial till

The SSDM technique is likely to be most useful when used together with other spatial data to understand the wider catchment. Here, it is assumed that high shear stresses passing through areas of glacial till (till-diamicton) are likely to result in high levels of deposition further downstream, where the valley gradient eases.

Starting near the head of the Kent catchment, Figure 5-1 shows substantial areas of high shear stress passing through areas of glacial till, and a high probability of deposition (yellow) further downstream. This agrees with the findings of the fluvial audit. Note that the glacial till has had a number of constraints removed from it, including existing woodland, and is based on the 100 m gridded slowly permeable soils model that was generated for the Working with Natural processes project (Environment Agency, SC150005). For full details of how this was derived, see Hankin and others (2018).

Figure 5-2 shows a similar situation downstream, with slope highlighted where the approach shines a light on valley-scale processes.

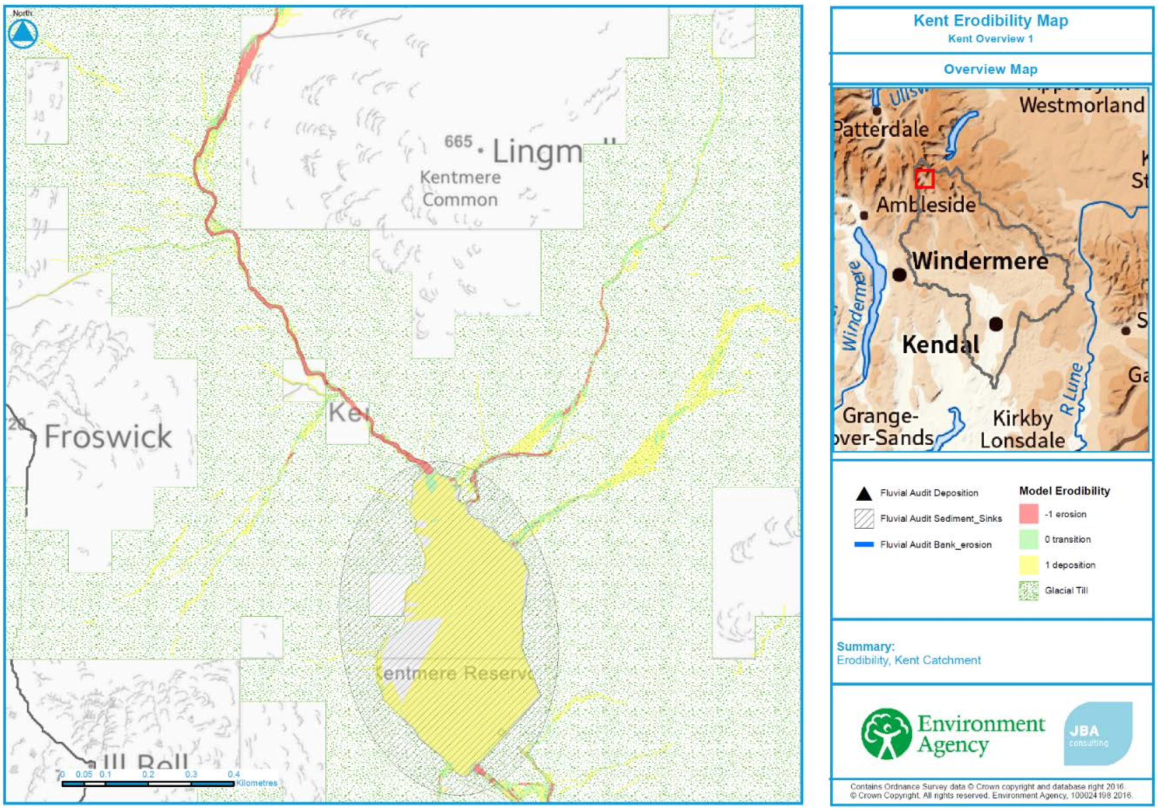

Figure 5-1 Kent - Areas of high shear passing through glacial till passing into lower gradient areas 1

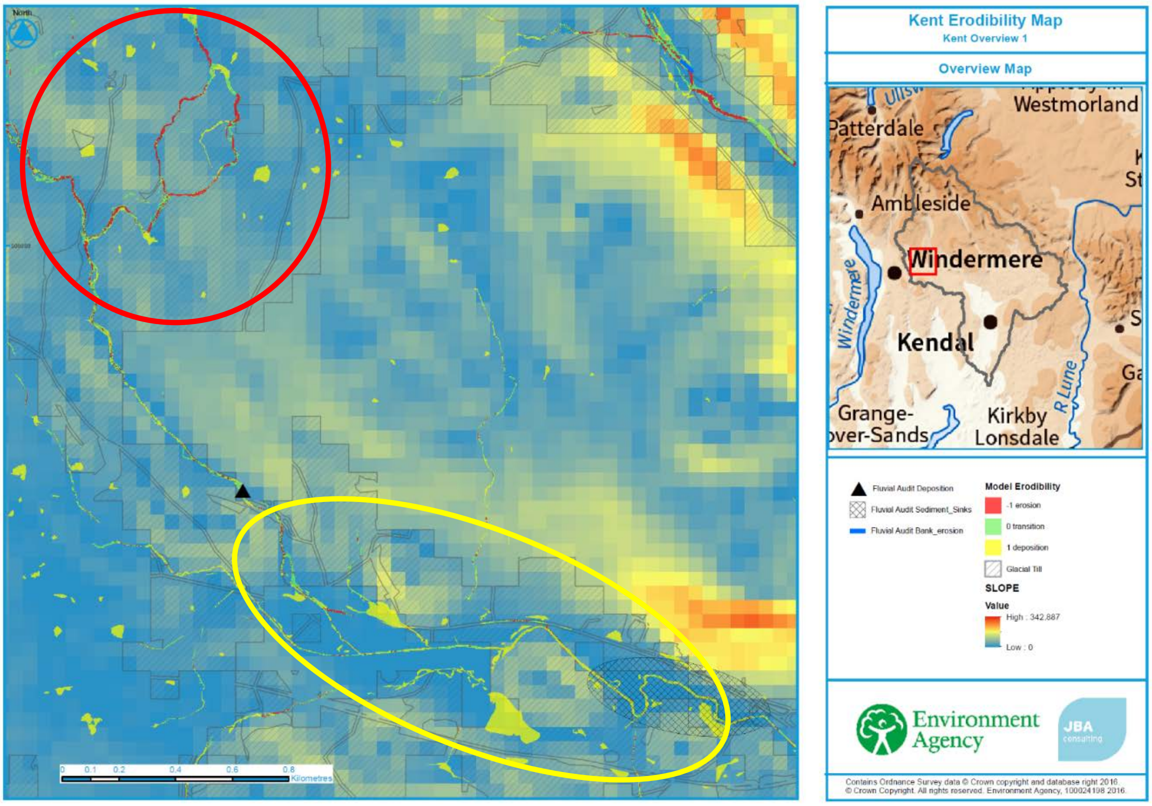

Figure 5-2 Kent - Areas of high shear on high slope passing through glacial till (red ellipse) passing into lower slope areas where deposition is predicted and observed (yellow ellipse)

Figure 5-2 is a good summary of a catchment-scale process that can be explained by overlaying the SSDM approach with other layers (here, slope and presence of glacial till without woodland).

5.2.2 Filtering out woodland

One improvement identified is simply to filter out a buffer of riparian wooded areas because woodland promotes bank stability**.** Figure 5-3 shows how an open data layer of woodland can be used to identify 'over-prediction' of bank erosion. First, a 4 m buffer is made of the OS Open Woodland data set (gold margin around woods). This would then be used to cookie-cut the high erosion potential from the river banks, but not the centre line where bed scour may still be possible.

In Figure 5-3, the fluvial audit only shows a short reach of eroding bank, whereas the SSDM method identifies high erosion near the banks for much of the wooded area. It is recommended that if the SSDM method is taken forward, the following 2 data sets are then used to cookie-cut the SSDM outputs:

- forestry inventory (most recent) buffered by agreed margin
- OS Open Woodland VectorMap (shown in figure) buffered by agreed margin

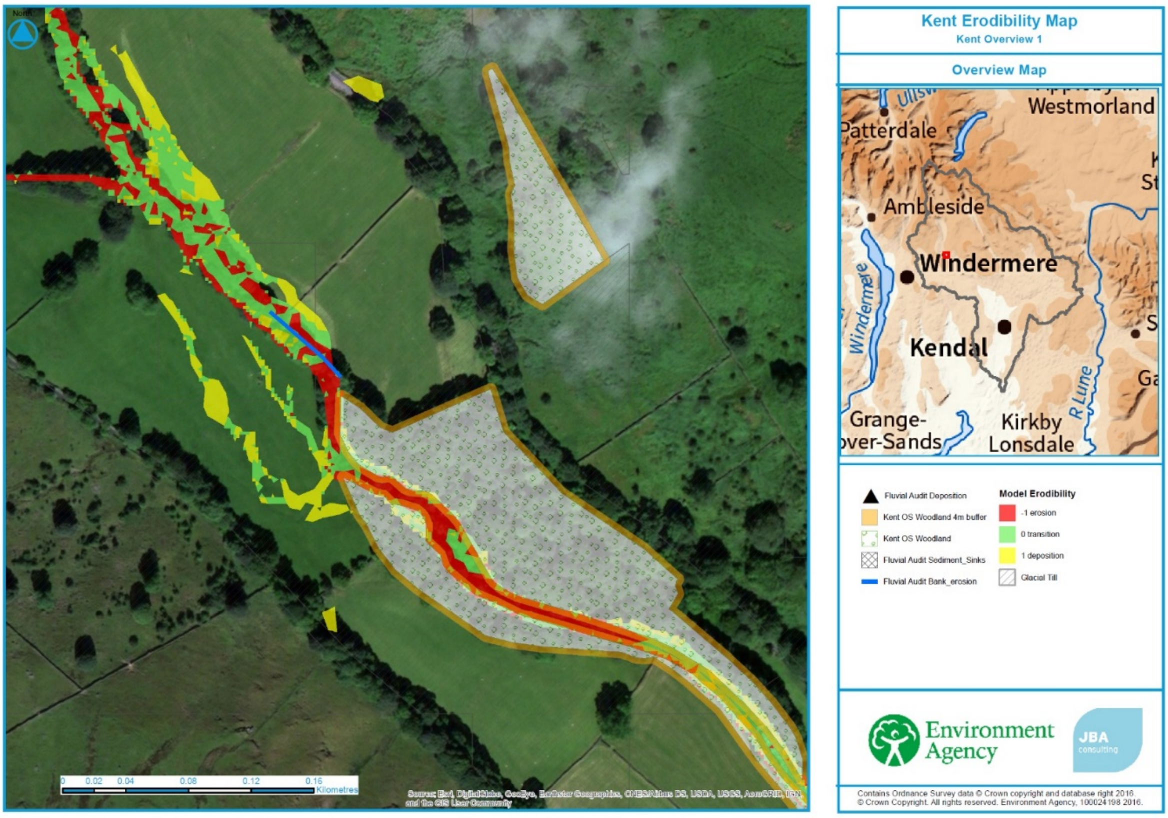

Figure 5-3 Kent - Improvement 2 - removing areas of high shear in areas of existing woodland

5.3 Model limitations

There are uncertainties in the results due to the input data and assumptions about model parameters. These are explained below.

- The SSDM erodibility maps are based on the RoFSW maps, including 3 storm durations (1, 3, 6 hour) and generated for 3 probabilities (3.33%, 1% and 0.1%). For each storm duration, the rainfall totals were based on the Flood Studies Report (FSR) depth-duration frequency (DDF) rainfall parameters on 5 km tiles spanning England and Wales. The maps are derived from maximum mosaics of the depths and velocities from the direct run-off and ReFH losses approach. This means that the predicted zones of erosion are averaged across different types of event, taking into account the peak depths and velocities that could occur for the same 3 probabilities, but having different durations.

  The RoFSW map was created in 2012 and is more accurate where there was LiDAR coverage, having an estimated root mean squared error (RMSE) of +/- 0.15m in the vertical. Areas of terrain without LiDAR were infilled with NextMap Britain, based on SAR data, which has a much larger RMSE or up to +/- 1m. This means that in places the flow accumulation lines are much less accurate than if they were derived with more recently obtained LiDAR. It is therefore worth overlaying the RoFSW map onto the most recent terrain data to check for inaccuracies. If the outputs form the RoFSW or the erosion analysis does not overlay the course of the river, then it is possible that the original terrain was incorrect.

- The parameters in the SSDM model (Shields constant, Mannings roughness, deposition factor, D50) are all uncertain, with ranges provided in earlier sections. Mannings roughness is dimensional and combines a range of energy losses, including turbulence.

  It is recommended that the user selects local knowledge or data (like grain size from a fluvial audit) to select an appropriate scenario from the 30 provided to reduce the uncertainty.

- There is no national map of grain size distribution. Therefore, a scenario library of erodibility maps was produced with a range of grain sizes (signified by D50) and Manning's n. If a national map of grain size distributions is developed, this could be used together with the scenario library to make a composite map of erodibility.

6 Climate change sensitivity testing

6.1 Overview

To create scenarios that could represent how the potential for erosion may change with climate change, the RoFSW model would need to be rerun to account for increases in rainfall.

This was not possible within the scope of the pilot study. Instead, the difference between existing surface water outputs for the 3.33%, 1% and 0.1% AEP rainfall events has been used to simulate climate change, and this is described in the following sections.

6.2 Approach

To simulate the effects of climate change, a series of sensitivity maps was generated to assess how the potential for erosion changes with increased rainfall.

The changes in total rainfall used to derive the 3 surface water map outputs for the 0.1%, 1% and 3.33% AEP events were analysed. This showed that the difference in total rainfall in the 1% to the 0.1% AEP was large (greater than 100%), and that the changes between 3.33% and 1% AEP rainfall totals was approximately 40% higher (Figure 6.1) (range is between 32 and 44%).

This 40% increase is similar in size to the projected increase in rainfall intensity for 2080 in the climate impacts tool (Environment Agency, 2019) and the projected UKWIR rainfall increases (UKWIR, 2017). Therefore, the difference in the 3.33% and 1% AEP erodibility maps was used to simulate the impacts of climate change. These figures should be revisited once analysis of UKCP18 data on rainfall uplifts is available.

6.3 Results

The results show that the expected increase in rainfall with climate change will lead to higher flows, which, in turn, will lead to higher depths and velocities. The analysis summarises a large increase in the extent of predicted zones of erosion by 2080.

Figure 6.1 provides a heat map of the increase in total rainfall averaged over 25 km^2 tiles covering England and Wales, based on the values used to produce the 1% AEP and 3.33 % AEP surface water flood maps in the RoFSW maps. There is a hydrological gradient that should be considered when assessing the changes.

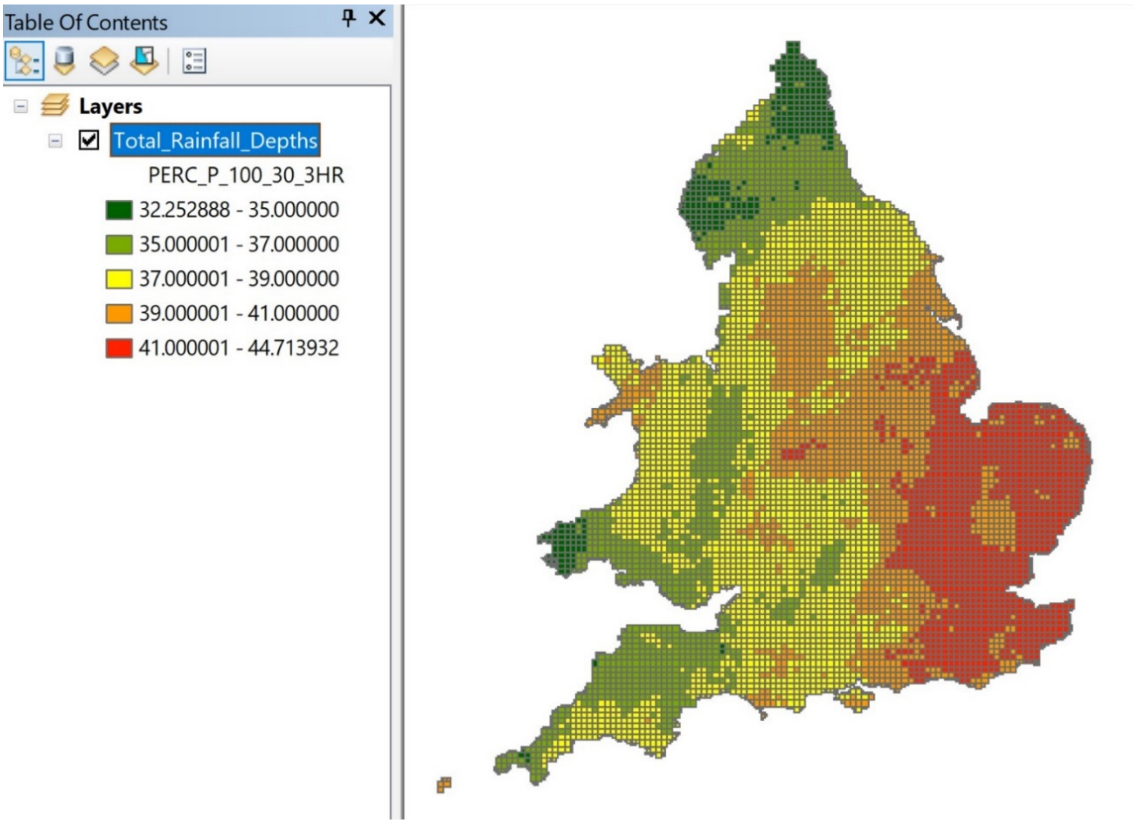

Figure 6.1 Changes in rainfall totals used in the original RoFSW maps

The area of cells identified as at risk of erosion for each scenario was combined into the 5 km tiles used for the RoFSW maps for all 10 of the scenarios and for the 1% and 3.33% AEP. The difference in areas of potential erosion was then derived and attributed to the 5 km tiles, named as follows:

- DIFF_EROD_S1_RP100_30
- DIFF_EROD_S2_RP100_30
- …and so on for 10 scenarios

These attributes were then used to colour theme the national 5 km tiles again, as shown for scenario 2 in Figure 6.2, resulting in a heat map of climate change sensitivity. Here, the cells at the red end of the green-yellow-red colour ramp indicate tiles with the largest predicted increase in zones of erosion.

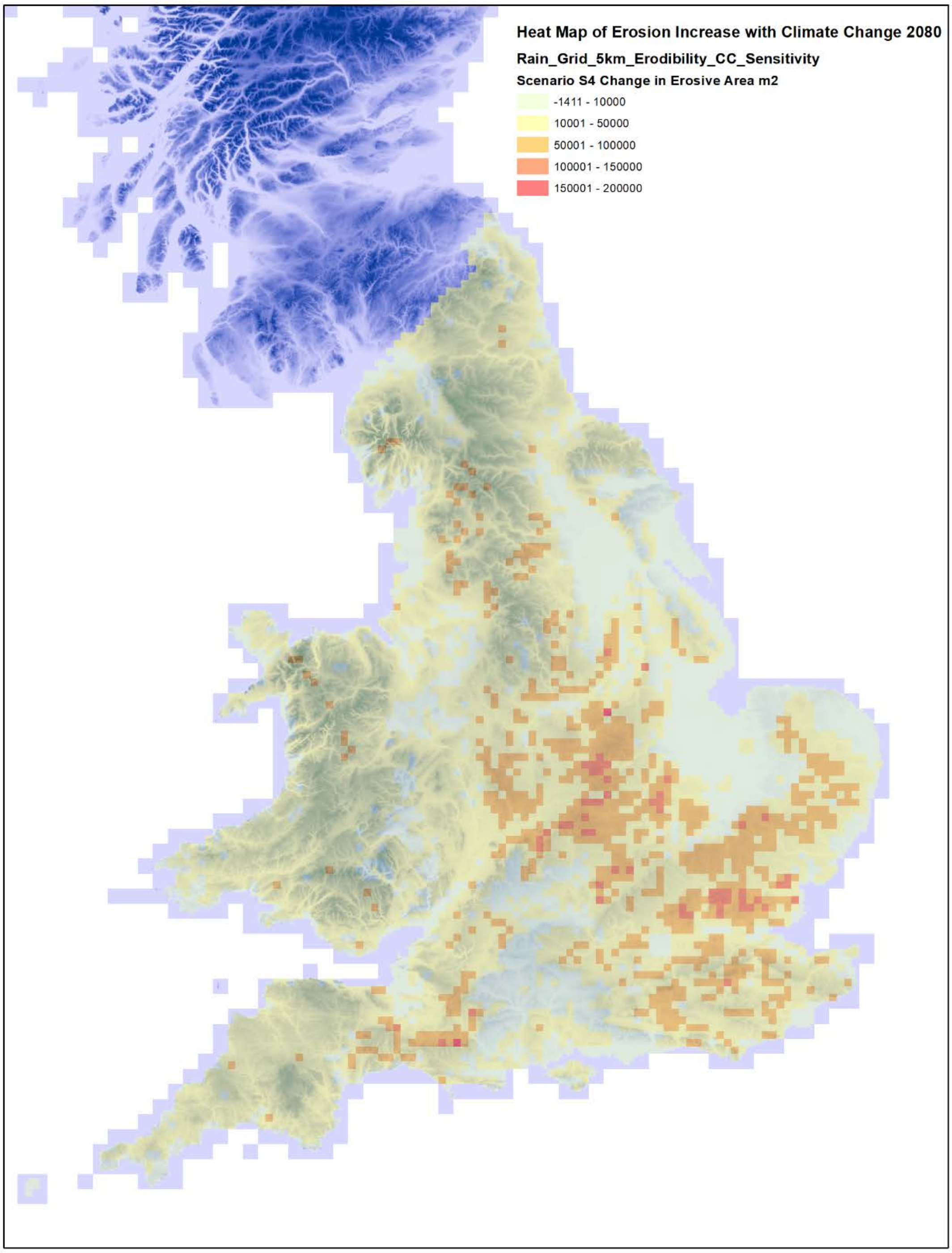

Figure 6.2 Climate change sensitivity heat map of areas of potential erosion for scenario 4 (D50=0.05 n=0.07)

Figure 6.3 demonstrates how the heat maps are produced. It is zoomed in on an area in Cumbria, where there is a large difference in the areas of erosion between the 3.33% AEP scenario map (black) and the 1% AEP map (cyan). This can be seen in the underlying data where the cyan zones are larger and represent a large increase in areas of potential erosion in the 1% AEP scenario, which simulates the impact of climate change on the erosion predicted for the 3.33% AEP.

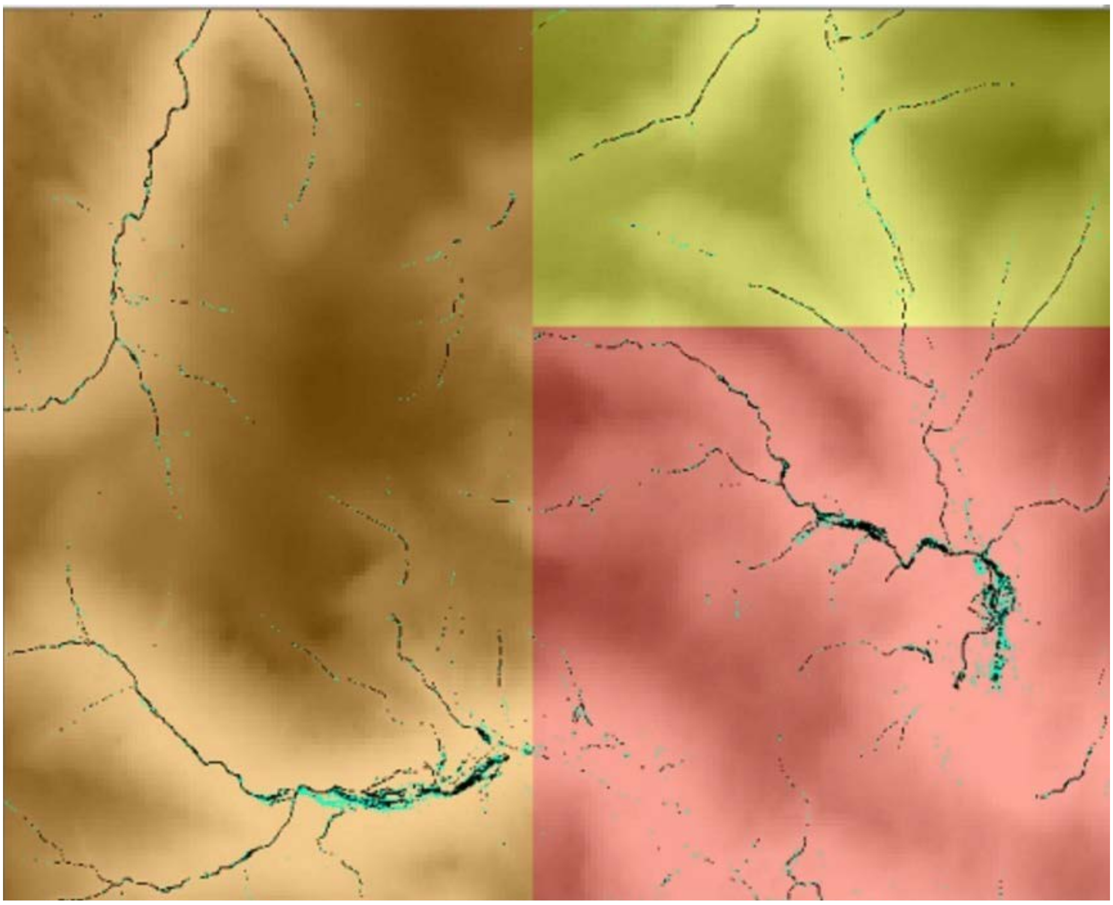

Figure 6.3 Zones of erodibility for scenario 9 (1% AEP in turquoise, 3.33% AEP in black)

The increase in areas of potential erosion for all 10 scenarios are quantified in the next section.

6.4 Increases in area of potential erosion due to climate change for England and Wales

The national increases in the area of potential erosion are reported in Table 6-1 across the 10 scenarios. Since there are no current national maps of the grain size D50 nor Manning's n, the average increase in area of potential erosion across all 10 scenarios has been derived in Table 6-2.

Table 6.1 Predicted increase in area of potential erosion for 2080

Scenario	1	2	3	4	5	6	7	8	9	10
D50	0.08	0.06	0.05	0.05	0.025	0.025	0.01	0.005	0.002	0.002
n	0.05	0.05	0.05	0.07	0.05	0.035	0.05	0.03	0.02	0.015
Increase in area of potential erosion (km2)	202.2	297.5	366.9	626.2	633.5	358.8	951.2	595.5	552.2	675.0

Table 6.2 Average increase in area of potential erosion 2080

Average increase in area of potential erosion across scenarios (km2)	525.9
Average increase in length of erosive channel assuming average width of 5m (km)	**105,180**

The estimated increase in area of erosion of 526 km^2 represents 0.33% of the modelled area of England and Wales. Assuming an average channel width of 5 m, this represents an average expected increase in potential erosion of 100,000 km of channel length compared with the present day. The Environment Agency's Detailed River Network (DRN) contains 257,000 km of watercourse, and while this is a useful comparison, it is not realistic to derive a percentage here as the RoFSW map represents more channel than the DRN. However, these figures represent a stark increase in the potential for erosion due to global heating.

7 Summary and recommendations

7.1 Summary

This project has explored how to produce, for the first time, national scale maps showing the potential for erosion in rivers across England and Wales.

A shear stress data mining method has been tested for England and Wales to produce mapped zones of erosion, deposition and transition. These are based on the physics of sediment mobilisation informed by realistic hydraulic computations using the JFlow ® (Lamb and others, 2009) solution of the 2D shallow water equations on a 2 m grid.

It has used the depth and velocity grids at 2 m resolution from the RoFSW model to generate shear stresses, together with relationships that determine how likely sediment in river channels is to move, depending on the shear stress and grain size.

A scenario library of maps has been produced for England and Wales. This includes 10 scenarios covering a range of assumed grain sizes and corresponding river bed roughness, for the 3 annual rainfall probability events used for the RoFSW maps (3.33%, 1% and 0.1%). Local estimates of grain size and roughness can be used to select the appropriate scenario relevant to local conditions or data use.

The 3 different probabilities for each scenario can be interpreted in a similar way to the RoFSW probability maps. For example, the erosion zones for 0.1%, 1% and 3.33% can be interpreted as bounding the zones of very low, low, medium and high risks of erosion, respectively.

Computations to consider the difference between scenarios were used to highlight potential increases in erosion due to climate change. The increase in total rainfall between the 3.33% AEP precipitation and the 1% AEP is approximately 40%, similar to the projected changes in the climate impacts tool for 2080 (Environment Agency, 2019). These 2 scenarios were compared to simulate the expected increases in rainfall intensity until 2080, demonstrating how the areas susceptible to erosion may change.

Across 10 scenarios, the average increase in area of potential erosion is 526 km^2, representing **0.33% of the modelled area of England and Wales**. Assuming an average channel width of 5 m, this represents an average expected increase in potential erosion of 100,000 km channel length by 2080 compared with the present day. These figures represent a large increase in the potential for erosion due to global heating.

The scenario output maps have been provided in raster format (within an ArcGIS 10.4 file geodatabase) for further analysis and to use for future flood risk management.

7.2 Recommendations

To create a model and maps that cover England and Wales some assumptions were made in the underlying input data sets and in the SSDM modelling method.

The scenario library of maps produced by this project should be used with an understanding of the underlying assumptions and uncertainties in the original model data. It should be noted that the RoFSW maps are more accurate where LiDAR data was available in 2012. Where it was not available (most locations outside of urban centres), the hydrodynamic modelling relied on terrain based on SAR data, which is less accurate in the vertical. When using the scenario maps, it is therefore advisable to overlay a range of map layers, including detailed river network, satellite imagery and the RoFSW layers. Misalignment of the predicted zones of erosion from the watercourse network will help highlight where the terrain used for the RoFSW was not accurate.

The SSDM method and scenarios have made assumptions about the grain size of material in the rivers and other parameters that can affect how likely a river bed is to be susceptible to erosion. Local knowledge or other data on actual grain size and bed material should be used where possible to select the scenario(s) that best reflect(s) local conditions (based on D50 grain size and Manning's roughness). To improve the modelling and local validation, a national map of D50 could be generated.

The climate change sensitivity maps also have uncertainties associated with them. Although some of the errors will have been reduced by combining the 2 m grids with the 5 km scale, there may be local areas at smaller scales where the changes to the zones of erosion are large but not reflected at the 5 km scale.

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List of abbreviations

AEP	Annual exceedance probability
JBA	Jeremy Benn Associates
LLFA	Lead local flood authority
DEM	Digital elevation model (typically unfiltered LiDAR)
DTM	Digital terrain model (typically filtered LiDAR)
LiDAR	Light Detection and Ranging – used to collect DEM
RoFSW	Risk of Flooding from Surface Water (maps)
RoFSW	Risk of flooding from surface water
SSDM	Shear stress data mining
RMSE	Root mean squared error
SAR	Synthetic-aperture radar used to fill in 5 m resolution caps in DTM
JFlow ®	JBA Consulting 2D Shallow Water Equation solver
UFMfSW	Updated Flood Map for Surface Water, later renamed to the RoFSW
UKWIR	UK Water Industry Research

Glossary

Term	Description
ArcGIS	ESRI software – Geographical Information System.
Critical stress	Shear stress at which sediment for a particular grain size is mobilised and entrained into the river flow.
Erodibility/erosion zones	Areas where the predicted shear stress based on the RoFSW maps exceeds the critical shear stress for a particular grain size.
JFlow ®	JBA in-house 2D Shallow Water Equation Solver (Lamb and others, 2009).
Shallow water equations	The depth average flow equations that include frictional, gravitational and inertial terms.
Shields constant/relationship	Shields (1936) related a dimensional shear stress to particle Reynolds number.
Grain size	Diameter of sediment material.
Mannings roughness	n friction coefficient relating velocity to depth, slope and channel geometry in an open channel. It has dimensions of $TL^{-1/3}$
RoFSW model	Risk of flooding from surface water maps were developed and improved with feedback from lead local flood Authorities across England and Wales in 2012.
AEP	Annual exceedence probability.
D50	Median diameter of particles in a distribution.
ReFH	Revitalised flood hydrograph. Method that improved the Flood Estimation Handbook re-statement of the Flood Studies Report unit hydrograph approach based on catchment descriptors.
Shear stress	Force per unit area due to friction.
Deposition factor	Factor to distinguish between zones that are erosive and those where the shear stresses are not likely to cause mobilisation or scour.
FSR DDF	Flood Studies Report depth-duration frequency are the characteristics of design rainfall needed to fully define a given depth of rainfall over a given storm duration having a given return period.

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