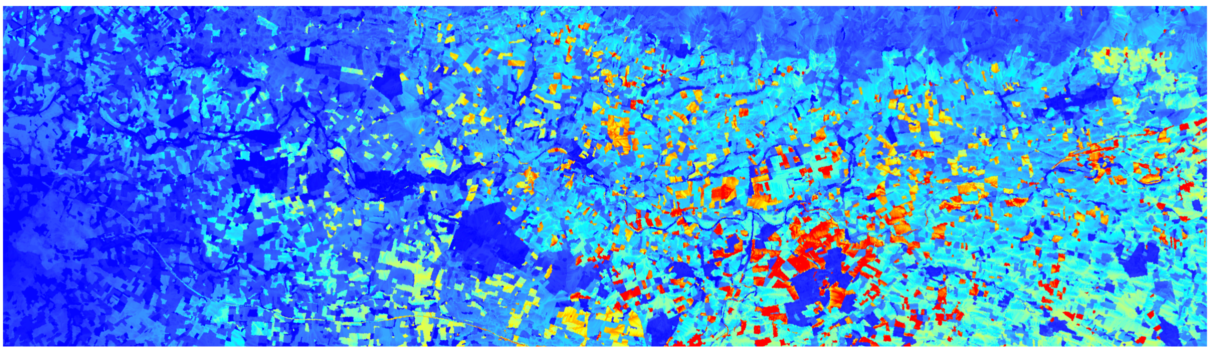
Spatial targeting of natural flood risk management within large river catchments: A nested approach of SCIMAP-Flood and CRUM3

Sim M. Reaney and Callum Pearson
Department of Geography
Durham University
Durham, DH1 3LE

sim.reaney@dur.ac.uk

Abstract
The paper presents a two stage workflow to identify where in the River Eden catchment are the optimal locations for implementation of natural flood risk management and how effective different NFM based schemes could be at reducing flood peak discharges. The first stage uses the prototype version of SCIMAP-Flood to give a risk based mapping of likely locations that are contributing to the flood peak. This tool uses information on land cover, hydrological connectivity, a set of different flood generating rainfall patterns and a set of hydrological travel time distributions to impacted communities. The risk mapping is applied at a 5m grid resolution for the whole River Eden catchment and hence provide sub-field scale information at the landscape extent. Therefore, SCIMAP-Flood can identify sub-catchments where physically based catchment hydrological simulation models can be applied to test different NFM based mitigation measures. In this paper, the CRUM3 model has been applied within an uncertainty framework to consider the effectiveness of soil compaction reduction and large woody debris dams within a sub-catchment. It was found that large scale soil aeration to reduce soil compaction levels throughout the catchment is probably the most useful natural flood management measure for this catchment.



SCIMAP-Flood for the central River Eden Valley

Introduction

Recent changes in the approach to flood risk management have shifted the focus from mitigation at the point of impact to a combined approach which includes managing the sources and pathways of flood waters. Previous studies (e.g. Wilkinson et al., 2010, Lane et al., 2011.) have shown the potential for natural flood risk management (NFM) in a range of settings and have developed a set of methods that can be applied to new catchments. However, the flood risk is not produced in a uniform way across a landscape and hence the effectiveness of a NFM measure will be a function of its location within the catchment with respect to:

- Local flood risk generation
- Hydrological connectivity to the river
- Travel times to the point of impact
- Spatial pattern of the rainfall event

Due to different storm events, antecedent hydrological conditions and land management each of these different factors will vary between storm / flood events. Therefore, it is important to recognise that the next flood will not be the same as the last and hence we need to manage for a range of probable scenarios.

To manage flood risk within a large river catchment, such as the River Eden (2300 km^2), there is a need to consider the spatial targeting at two scales: the whole of the River Eden catchment and the local sub-basin. With large catchments, there are multiple points of impact and hence a measure to reduce flood risk in one location may increase the risk in another due to changes in the sub-catchment timing and synchronisation. The different rainfall patterns and storm tracks will give different flood timing dynamics in each event. Therefore, there is a need to consider how these variables interact to give integrated spatial targeting maps for NFM which has the greatest chance of reducing flood risk over a range of possible future events. It is possible to apply simulation based hydrological and hydraulic models at the spatial scale of the River Eden but compromises must be made in the spatial resolution, number of events that can be considered or in the spatial extent of the simulations. Also, these models are computationally and financially expensive, which means within a standard cost:benefit flood scheme assessment approach, the money spent on the simulation modelling cannot be spent on the mitigation scheme. However, the details of the effectiveness of mitigation actions on flood magnitudes is required for the design and assessment of the schemes. This report therefore proposes a two stage approach to managing flood risk within the River Eden catchment:

- The use of spatially detailed, catchment wide, risk based mapping, accounting for rainfall patterns and points of impact, to identify key sub-catchments
- The application of detailed physically based models, within an uncertainty framework, within these identified locations to design and test the proposed NFM scheme.

Methods

The spatial targeting at the full river Eden catchment scale has been undertaken with the newly developed prototype SCIMAP-Flood tool and the detailed sub-catchment hydrological modelling has been implemented with the established CRUM3 catchment simulation model. The example for the sub-catchment modelling is the River Roe in the lower River Eden, which was impacted by flood events in 2005 and 2013.

Landscape Scale Spatial Targeting for NFM: SCIMAP-Flood

The suitability of a site for the implementation of natural flood risk mitigation measures is determined by the travel time of the flood waters to the point of impact, the spatial pattern of the rainfall depth pattern, the effectiveness of the land cover in generating rapid flood flows (overland, drains and near surface flows) and the strength the of the hydrological connectivity from the landscape to the river channels. This report presents the initial version of the new SCIMAP-Flood tool for spatial targeting of NFM measures at the landscape scale. This approach is based on the SCIMAP fine sediment risk mapping tool (Reaney et al. 2011) but expanded to capture the flood issues discussed in the introduction.

The SCIMAP-Flood tool assigns risk weights to each of the flood hazard driving factors and then combines these to give a point scale assessment of the potential value of slowing flows at that location for decreasing flood generation. This assessment is based on the critical source area concept whereby there needs to be both a generation of flood risk and an active hydrological connection to the river channel (Heathwaite et al. 2005). The source risk is determined as a function of travel times, rapid runoff generation potential and the rainfall pattern and the hydrological connectivity is determined by the Network Index (Lane et al 2004).

This implementation of SCIMAP-Flood has been undertaken for the full River Eden catchment (2300 km^2) using a grid resolution of 5m, giving a dataset of 12589 by 17236 cells, or 216 megapixels. This detailed assessment is required to capture the detail of the land management and the processes within the hydrological connectivity assessment. The detailed assessment means that it is possible to give sub-field level assessments of flood risk generation at the landscape spatial extent. This level of detail therefore enables land owners and managers to see the detail of their location and to be able to see their flood generation risk in the wider context of the whole landscape.

Travel Times

It is necessary to consider the travel times of the generated flood waters to the point of impact since the travel times are a key factor in determining the magnitude of the flood peak due to the synchronisation or not of the individual flood peaks from different parts of the catchment. The approach taken within SCIMAP-Flood is a simplified version geomorphic unit hydrograph (see Rigon et al. 2016) whereby the flow distance from different parts of the catchment are calculated based on terrain analysis. The hypothesis is that slowing the flow using NFM measures in the area of the catchment that contributes to the flood peak will have the most effective flood hazard reduction. The area that will contribute to the flood peak has been defined by the mean travel distance and is given the greatest weighting (a value of one). The other travel times are linearly rescaled based on the relative distance to the mean travel time. This approach has been implemented for three points of impact within the catchment, Carlisle, Appleby-in-Westmoreland and Kirkby Stephen, Figure 1.

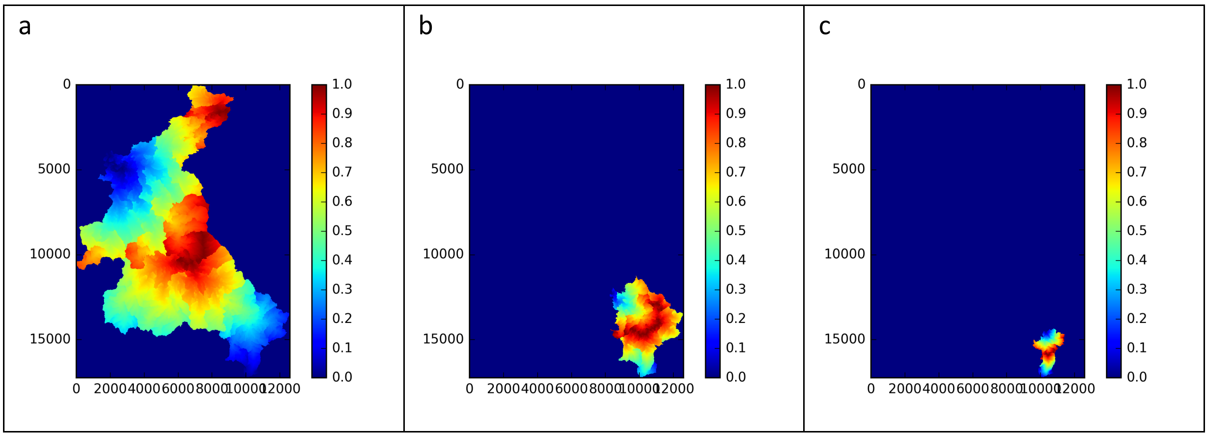


Figure 1 Travel time distributions for a, Carlisle, b, Appleby-in-Westmoreland and c, Kirkby Stephen. Legend unit are in relative travel time within the catchment

Future work could develop the weighting of different points of impact to consider where it may be beneficial to accelerate channel flows to make space for the following flood peak.

Local Runoff Generation

Local runoff generation is based on a combination of the land cover, land management, soil properties and slope gradient. There are however and number of cross-correlations between these variables which enables a simplification for the processes which is acceptable for a risk based, minimum information requirement, approach. Within this application, land cover has been taken as the dominate factor since the other key factors will co-vary with land cover. Within the SCIMAP-Flood framework, it is possible to include the other variables in an explicit rather than implicit way and the extra information from the use of additional datasets can be assessed in future work.
The spatial pattern of land cover has been based on a simplification of the CEH Land Cover Map 2007, as described in Table 1. The land cover pattern could be updated with more recent land cover information from open data sources, such as LandSat.

Id	Land Cover	Weight	Notes
1	Woodland	0.05	Woodland has been given a lower risk weight due to the high infiltration rates and lower saturation deficits within the soil
2	Arable	0.8	Arable has been assigned a high risk weight due to the widespread use of soil drainage that rapidly transfers water to the river channels.
3	Improved Grassland	0.3	Improved grassland has been given a high weighting than un-improved grasslands due to the likely compaction of the soils by livestock, which results in lower infiltration rates.
4	Unimproved Grassland	0.15	Unimproved grassland has been given a risk weight above woodland
5	Urban	1.0	Urban has been assigned a high risk weight due to the impermeable surfaces and effective drainage that rapidly transfers water to the river channels. Although not tackled directly with NFM, SuDS and elements of NFM could be applied.
6	Moorland	0.1	Moorland has been given a lower weighting than unimproved grasslands to reflect the more natural soil structure and low potential compaction.
7	Water and inland rock	0.0	Although lakes, rivers and inland rock will convert all of the rainfall water to runoff, it is not possible to modify this behaviour with NFM measures and hence water has been given a low value

Table 1 List of flood water generation risk weightings.

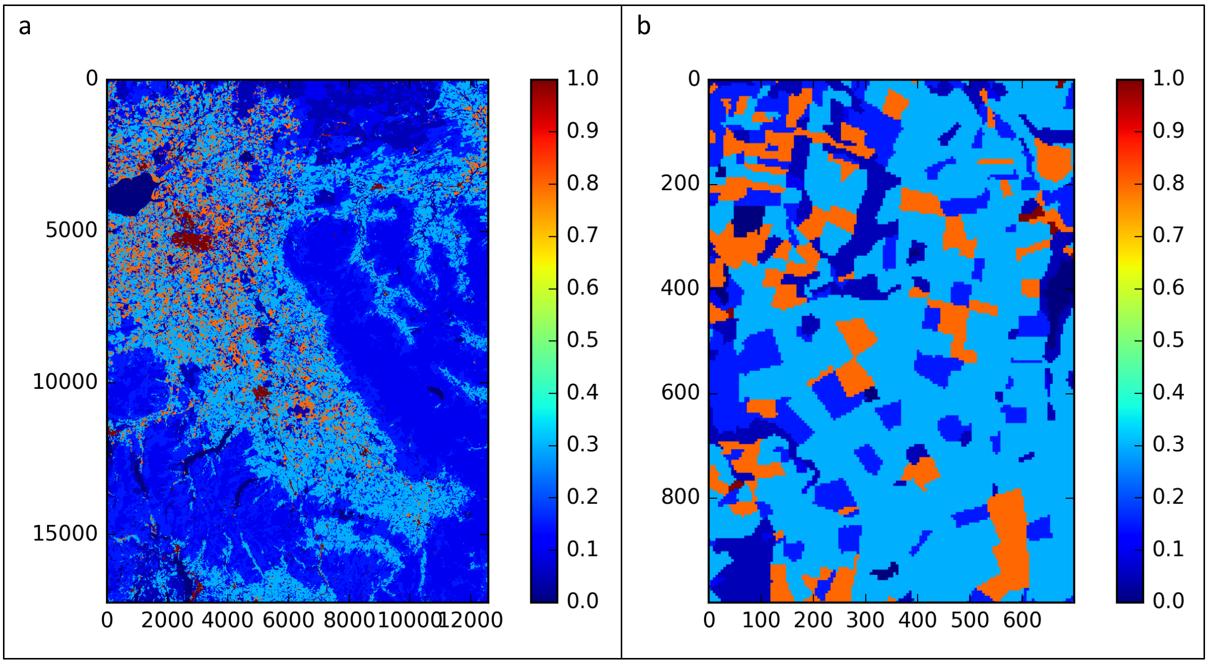


Figure 2 a, Land cover based flood water generation risk weights for the River Eden Catchment and b, detail of the runoff generation pattern for a 5km by 3.5 km area.

Rainfall Pattern

The rainfall patterns that have given rise to historical flood events within the River Eden catchment are based on the CEH Gridded Estimations of Areal Rainfall, GEAR (Tanguy et al. 2015). This dataset comprises daily rainfall estimates based on the observed rain gauges, presented in a 1kmx1km grid.

In this analysis, a set of rainfall patterns were selected based on the analysis of the National River Flow Archive for five stations across the River Eden catchment. The date of the top five peak flows for each of these stations were selected and after duplicate storms effecting multiple flow gauges have been removed, a set of 13 storms patterns were created, Figure 3.

Date	Stage (m)	Flow (m^3/s)	Location	Date	Stage (m)	Flow (m^3/s)	Location
09/12/1964	2.499	300.064	Udford	**01/02/1995**	5.149	811.842	Warwick Bridge
09/12/1964	4.883	719.134	Warwick Bridge	**20/02/1997**	4.715	666.567	Warwick Bridge
23/03/1968	5.93	1103.917	Warwick Bridge	**03/02/2004**	2.705	230.32	Great Musgrave
24/03/1968	6.266	1200	Sheepmount	**07/01/2005**	2.887	276.751	Great Musgrave
24/03/1968	4.04	662.999	Temple Sowerby	**08/01/2005**	7.226	1516.411	Sheepmount
24/03/1968	2.56	313.72	Udford	**08/01/2005**	4.33	925	Temple Sowerby
04/01/1982	5.583	957.453	Sheepmount	**08/01/2005**	2.846	399.39	Udford
21/12/1985	3.788	484.096	Temple Sowerby	**18/11/2009**	2.748	240.7	Great Musgrave
21/12/1985	2.533	307.563	Udford	**19/11/2009**	2.908	417.352	Udford
21/12/1985	5.093	793.493	Warwick Bridge	**20/11/2009**	5.813	1029.304	Sheepmount
24/02/1991	3.73	448.659	Temple Sowerby	**04/11/2010**	2.792	251.692	Great Musgrave
31/01/1995	3.88	544.561	Temple Sowerby	**08/12/2011**	2.902	280.878	Great Musgrave
01/02/1995	5.568	952.842	Sheepmount				

Table 2 Historical Flood Events within the River Eden Catchment

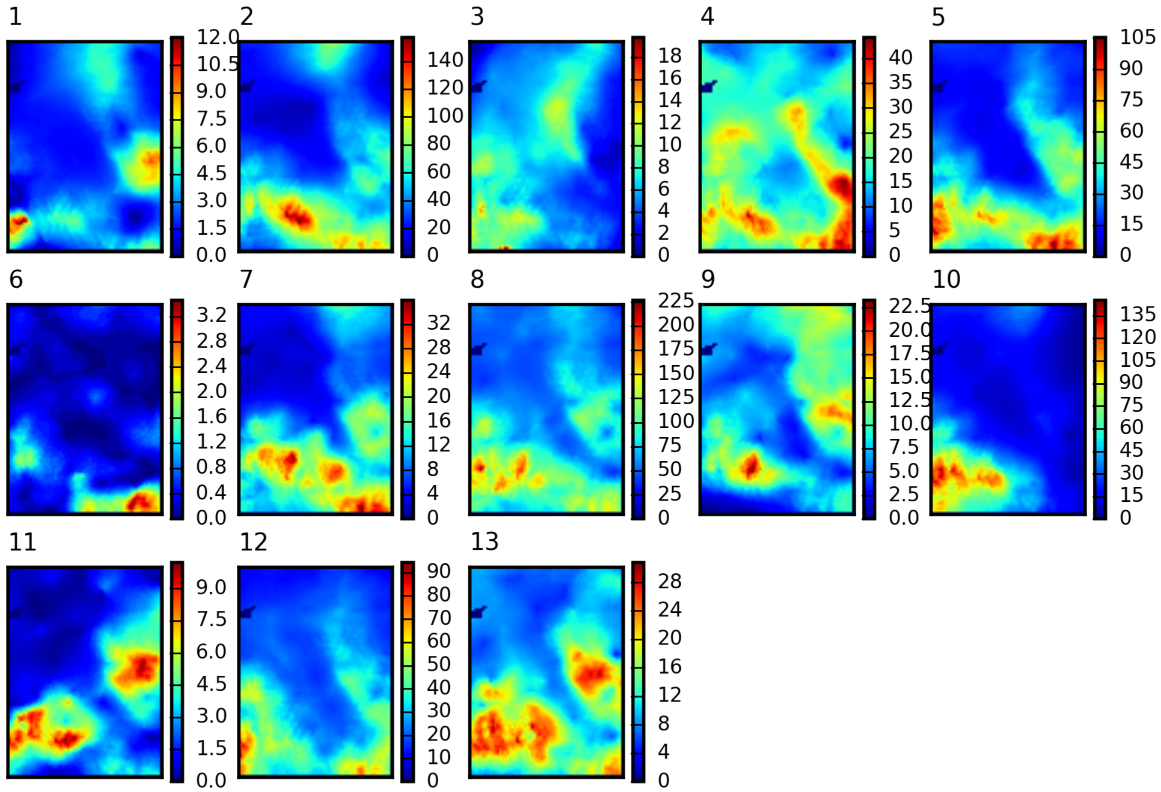


Figure 3 Different rainfall patterns based on CEH GEAR 1km rainfall data. Legend units are in mm day^{-1}

Hydrological Connectivity

The connectivity is represented with the Network Index (Lane et al. 2004). This index is derived from the analysis of a detailed digital elevation model, in this application the 5m NextMap dataset has been used. The analysis is made up to two steps: Firstly, the propensity for runoff generation at each point in the landscape is calculated using the topographic wetness index (Beven and Kirkby, 1979). This calculation determines the wetness and runoff generation characteristics for each point in the landscape as a function of the upslope contributing area and the local slope gradient. The second step uses a flow path tracing algorithm to analyse the runoff transmission characteristics of the points on the downslope flow path to the river or lake. This flow tracing determines the landscape scale wetness required for each point to be capable of generating runoff and for there to be a connected pathway to the river or lake. This index gives the relative pattern of connectivity potential across the landscape.

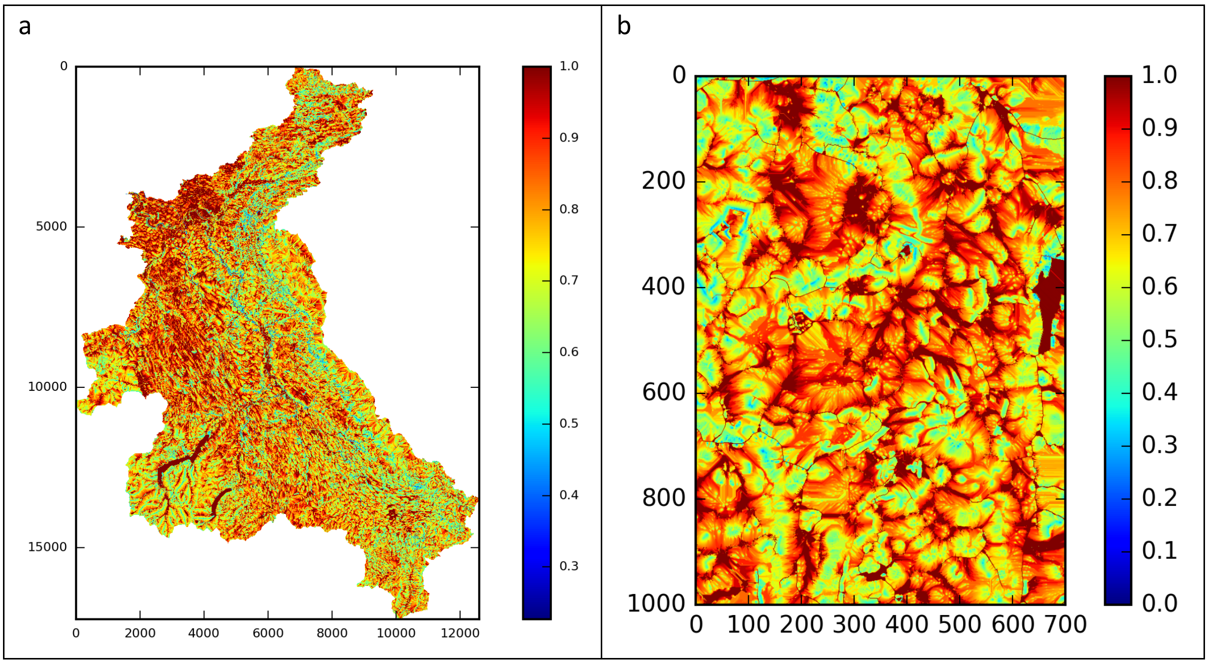


Figure 4 a, Relative hydrological Connectivity for the River Eden catchment and b, detail of the hydrological connectivity patterns. A value of 1 represents the most connected areas and a value of zero represent the least connected areas.

Integration of factors

The different rainfall patterns, travel times and flood risk generations are combined to give a single integrated assessment of the locations most suitable for the implementation of NFM. The flood risk (F) is determined by:

$$F = \sum_{n=15}^{rf} \sum_{n=3}^{tt} L.R.C.T$$

Where *rf* is the rainfall map, *tt* is the travel time map, *L* is the land cover flood generation risk, *R* is the rainfall pattern, *C* is the hydrological connectivity and *T* is the travel time factor. This analysis gives a map of the flood risk generation risk at the 5x5m grid cell resolution.

Sub-Catchment Scale Spatial Targeting for NFM: CRUM3

Having determined the points of impact requiring reduction in flood peaks from different rainfall/ land cover scenarios, this next part of analysis uses the CRUM3 hydrological model to investigate targeting of land use management/changes. CRUM3 is a fully distributed, object orientated, process based hydrological model which operates at a landscape scale in surface water dominated catchments (Lane et al., 2009). It was designed to address questions related to the impact on flow extremes from projected climate change and land management techniques whilst using a minimal parameter set derived from accessible national datasets (Lane et al., 2009). CRUM3 consists of four key elements; weather, 1D vertical hydrological processes, landscape processes and the river channel network, Figure 5.

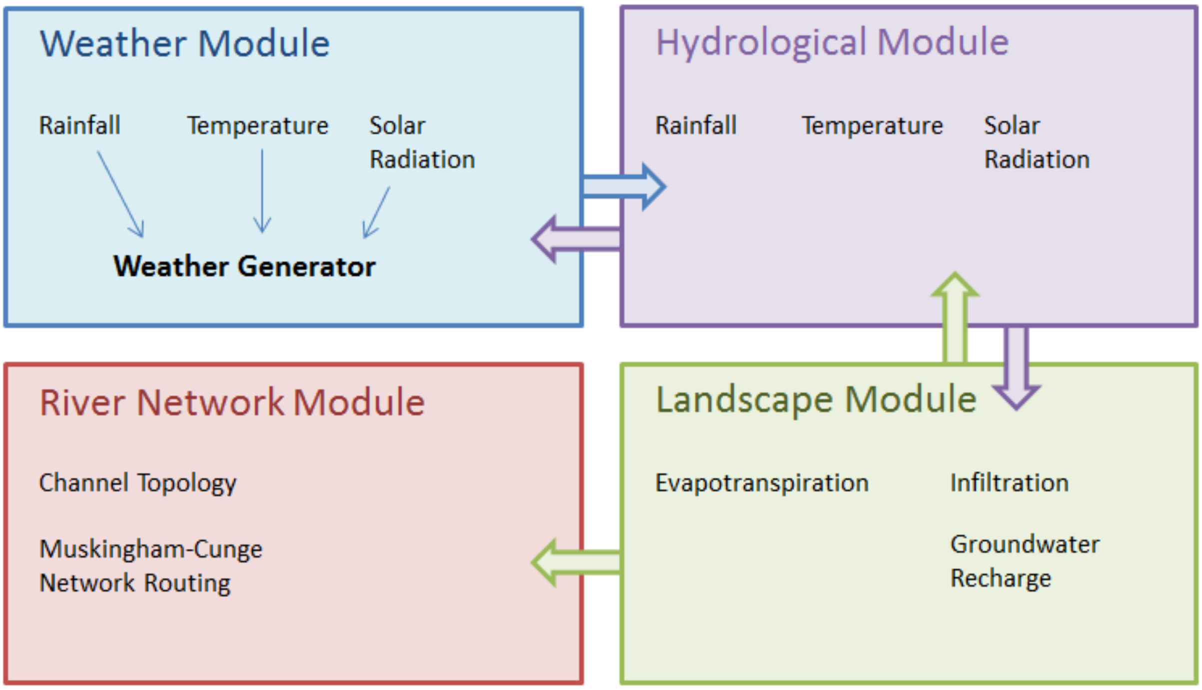


Figure 5 Representation of the structure used in CRUM3

The model was used within the GLUE predictive uncertainty estimation framework (Beven and Binley 1992). The uncertainty estimation experimental design was based on a Latin hypercube with 5014 parameter sets tested. The top 30 ranked GLUE runs, and thus the 30 most suitable land cover and soil parameter sets for simulating the hydrological regime of the River Roe catchment, were taken forward for the application of the flood risk reduction scenarios. Within this report, the results for soil compaction management through aeration and the implementation of woody debris dams are presented.

The River Roe catchment

The River Roe catchment has a small population, centred around the villages of Stockdalewath and Ivegill, and is predominantly agricultural with regards to land cover with 82% of the catchment land either improved grassland or arable. The majority of the soil within the catchment is agriculturally productive and drains to the channel network. The channel network consists of two tributaries

(River Ive and River Roe) that form the River Roe at Highbridge. The River Roe drains the west of the catchment and is formed from a series of wooded gills and streams that drain the steeper high ground to the west of the catchment. The River Ive is a flatter catchment with gentler terrain that drains the agricultural land to the centre and east of the catchment. There is a high slope gradient around the channel network of the River Roe with a limited floodplain and thus minimal opportunity for flood water to be stored as it flows downstream.

The key description of the River Roe catchment is:

- The catchment area is 63 km^2 to the flow gauge
- The highest slope gradient is concentrated around the channel network and the areas of higher elevation with a maximum gradient of 48.5°, Figure 6
- The majority of the catchment is used for agriculture with 82% of the catchment classified as improved grassland for livestock grazing and arable for cereal production, Figure 7 and Table 3.
- The maximum river flow at the gauging station was 98.8m^3/s which was recorded on 8th January 2005, Figure 8.

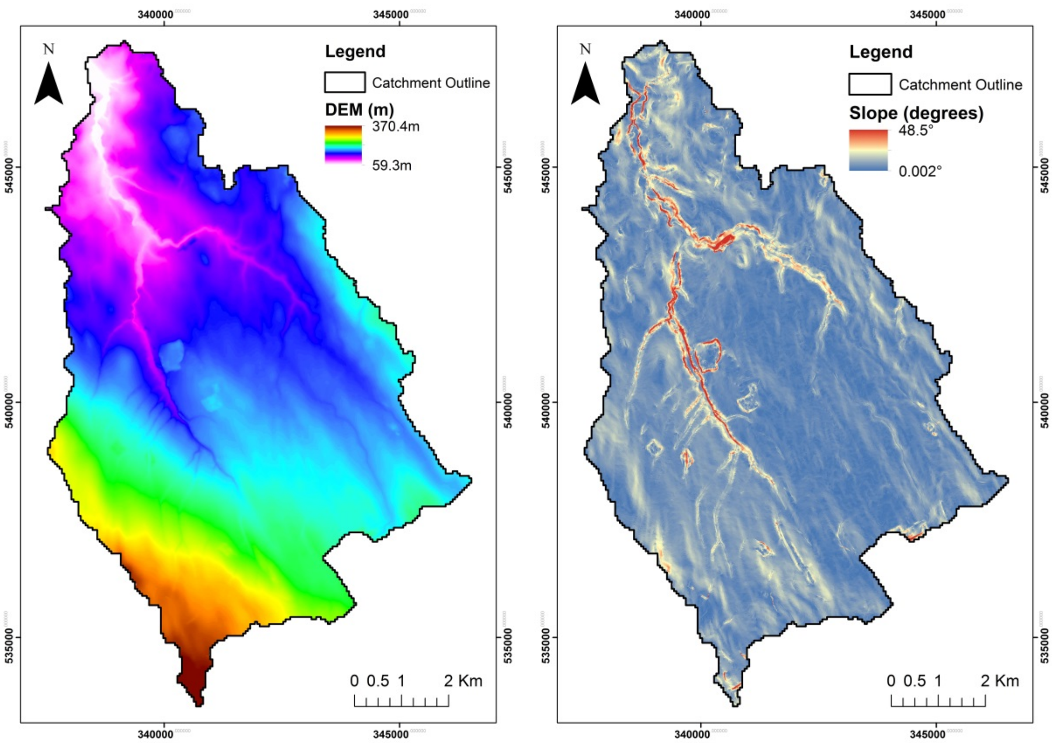


Figure 6 (left) is a DEM of the River Roe catchment showing elevation. Right map shows the slope in the River Roe catchment. Both derived from 5m resolution data Nextmap data from Intermap.

LCM2007	LCM2007 Class	% of Coverage
1	Deciduous Wood	5.13
2	Coniferous Wood	2.85
3	Arable and Horticulture	23.90
4	Improved Grassland	58.08
5	Rough Grassland	7.86
6	Neutral Grassland	0.08
8	Acid Grassland	1.13
10	Heather	0.21
11	Heather Grassland	0.07
14	Bare Ground	0.38
22	Urban	0.14
23	Suburban	0.17

Table 3 Percentage land cover for the LCM2007 categories in the River Roe catchment

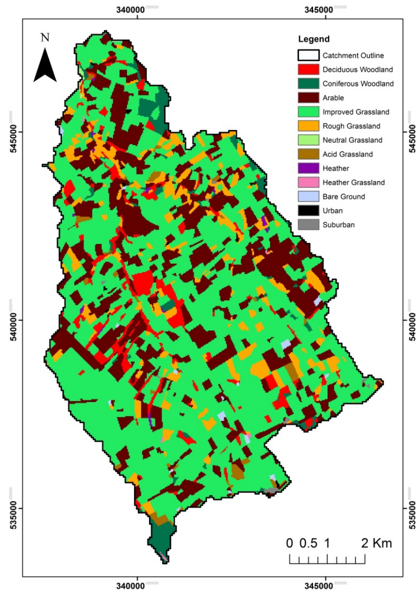


Figure 7 Land cover map for the River Roe catchment created using LCM2007 data (Centre for Ecology and Hydrology, 2015)

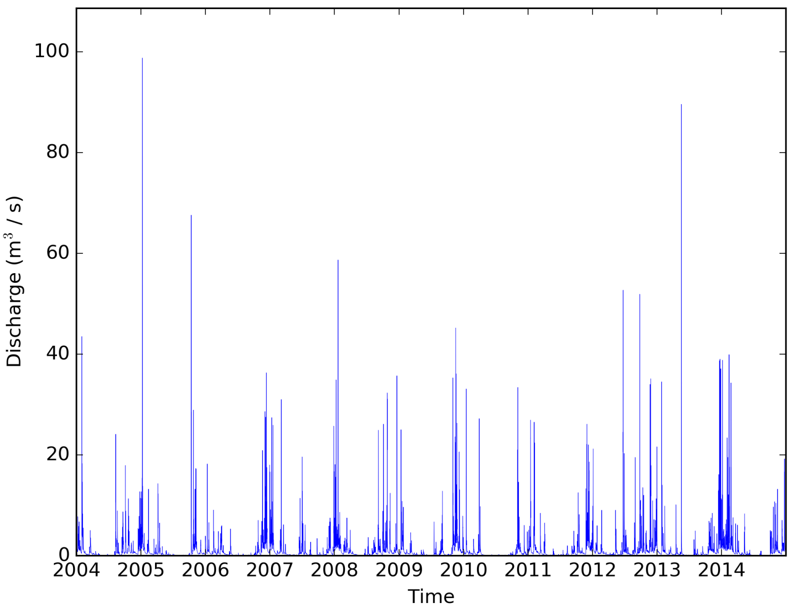


Figure 8 A time series of 15 minute flow data for the River Roe at the Stockdalewath gauge for the period 2004 to 2014.

Modelling NFM Schemes using CRUM3

Previous research has recognised the impact of soil compaction on both flood peaks and low flows (Boardman, 2003; O'Connell et al., 2007; Posthumus et al., 2008; Pattison, 2010; Smith, 2010). With the improved grassland and arable land cover categories dominating the land use in the River Roe catchment there was a need to simulate the effects of reducing the compaction levels through soil aeration and livestock grazing management. This was achieved in CRUM3 by altering the soil parameters of both the arable and improved grassland land cover categories. The compaction was modelled with scenarios changing both categories at a catchment scale. The values of soil porosity, soil depth and saturated conductivity were changed to simulate changing infiltration rates and the impact this has on discharge. The rate of change in compaction levels was created using Low, Medium and High compactions levels from Pattison (2010). The scenarios were developed to assess the impact of soil aeration at reducing flood risk in the Roe catchment were targeting at certain land covers. These scenarios altered the entire area of the arable and improved grassland land cover categories from their assumed current compact level to an aerated compaction level; this was done with three scenarios using all the arable area (23.91% catchment area to be aerated), all the improved grassland area (58.54%) and the combined arable and improved grassland area (82.45%).

Large woody debris (LWD) dams can slow and divert flood discharge onto the surrounding woodland floor and offer an artificial approach to a natural process; they target peak discharge in small ditches and channels and a cumulative approach can reduce peak flood flow (Environment Agency, 2011; Quinn et al., 2013). LWD dams store and attenuate water during high flow events with each LWD dam, surrounding channel and floodplain morphology reacting differently with regards to flow attenuation (Forestry Commission Wales, 2007). There is the possibility to place LWD debris dams at regular intervals in the channel and for extensive reach lengths; Forestry Commission Wales (2007) state a LWD dam can be placed every 7 to 10 channel widths with Nisbet et al. (2011) ascertaining that the channels should not be greater than 5m in width.
LWD have been represented in CRUM3 through the ability to restrict flow to a set value for selectable channel reaches in the channel network. To develop scenarios for quantifying the impact of LWD dams on maximum discharge (MaxQ) in the Roe catchment the Strahler stream order was applied to the channel network (Figure 9). Scenarios were developed where channels with a Strahler number of 1, 2 and 3 had LWD dams applied.

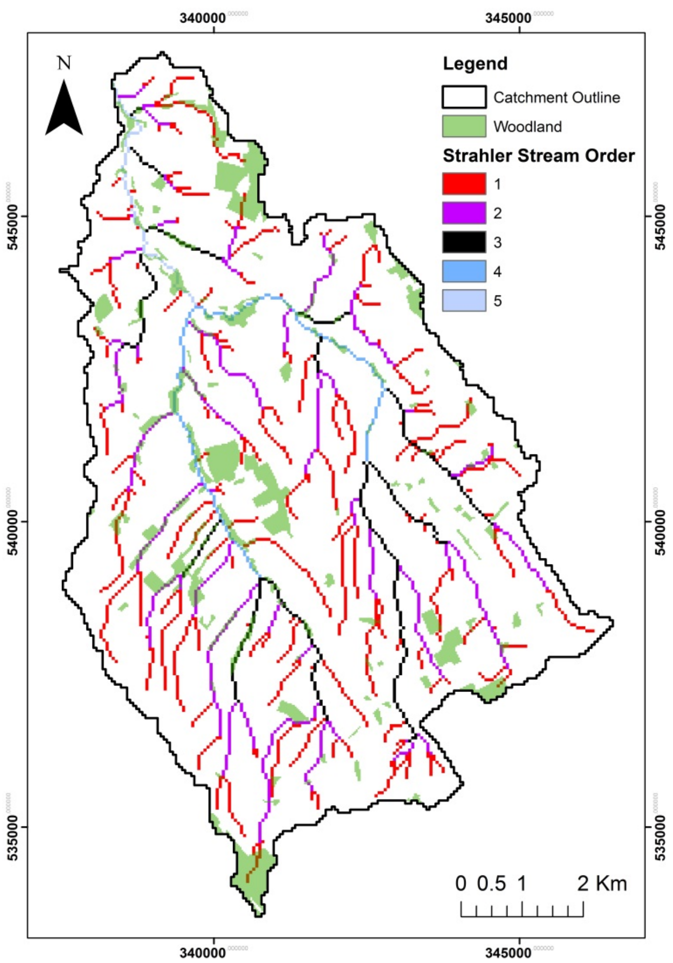


Figure 9 The Strahler stream order in the Roe catchment and the areas of deciduous and coniferous woodland

To define a value simulating the effect of LWD flow restriction to the selected wooded channel reaches the maximum discharge characteristics of each Strahler number was calculated from the model output. This calculation gave 1.99m^3 s^{-1} for Strahler order one channel cells, 4.49m^3 s^{-1} for Strahler order two channel cells and 5.29m^3 s^{-1} for Strahler order three channel cells.

The potential reduction in maximum discharge allowed through a restricted channel reach was calculated using values from Wenzel et al. (2014). Their research found an average peak discharge of -2.2% under LWD conditions with additional peak flow reduction values of -25% and -40% acquired through high flow threshold testing. The three flow reduction percentages were applied to the catchment-wide average maximum discharge values for each Strahler number (Table 4.2).

	Original (m^3/s^{-1})	-2.2% (m^3/s^{-1})	-25% (m^3/s^{-1})	-40% (m^3/s^{-1})
Strahler 1	1.99	1.94	1.49	1.19
Strahler 2	4.49	4.39	3.36	2.69

Strahler 3	5.29	5.17	3.97	3.17

Table 4 Catchment-wide average maximum discharge created from ten randomly selected wooded channel reaches from the corresponding Strahler number and the restricted maximum discharge flows for each Strahler number using Wenzel et al. (2014).

For each of the three peak flow reduction percentages seven flood risk reduction scenarios were created to represent LWD dams at a catchment scale. Using Strahler numbers these scenarios were all the wooded channel reaches with a Strahler number of 1, 2, 3, 1 and 2, 1 and 3, 2 and 3 and all three values.

Within this report, only the compaction and LWD results are represented. Further scenarios for Roe Beck are available in Pearson (2016). The CRUM3 model is capable to representing a wide range of different NFM based mitigation options, both individually and in combination.

Results

Landscape wide results from SCIMAP-Flood

The results from SCIMAP-Flood at the spatial resolution of 5mx5m are shown in Figure 10. This figure shows the results for all points of impact (Carlisle, Appleby-in-Westmoreland and Kirkby Steven). This map can be contrasted with the results for a single point of impact at Carlisle, Figure 11. The consideration of the multiple points of impact weights the likely areas to the upper River Eden valley since these locations have the potential to benefit all three points of impact. Within this proof of concept application, all three points of impact have been given equal weighting and this assumption could be updated to reflect the number of properties and businesses at risk in each settlement. The rainfall patterns are reflected in the focusing of the flood water generation risk in the southern section of the catchment. There are also large areas of connected improved grassland and area that are also predicted to be important for generating flood risk. The land cover weights represent flood risk, focus the results on the urban areas due to their high runoff and connectivity. The risk weights could be developed further through the use of the SCIMAP-Fitted approach (see Reaney et al. 2011 and Milledge et al. 2012). Figure 12 shows field scale detail of SCIMAP-Flood for the River Roe area.

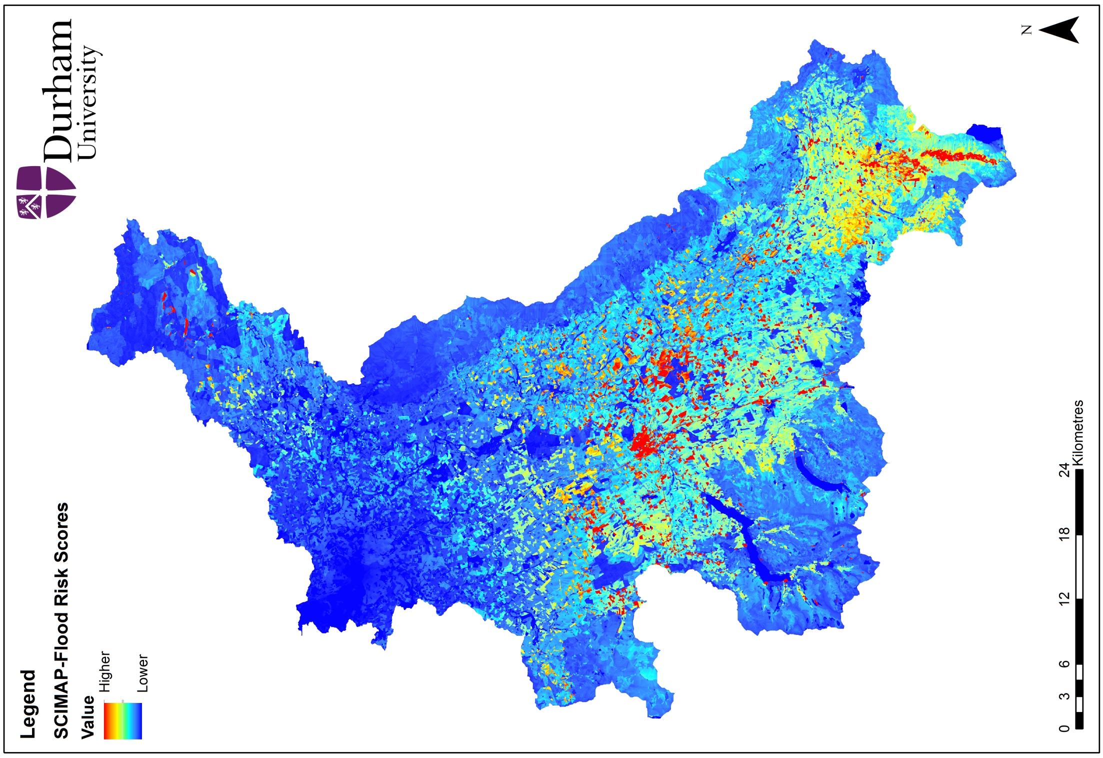


Figure 10 SCIMAP-Flood for the River Eden catchment for all points of impact

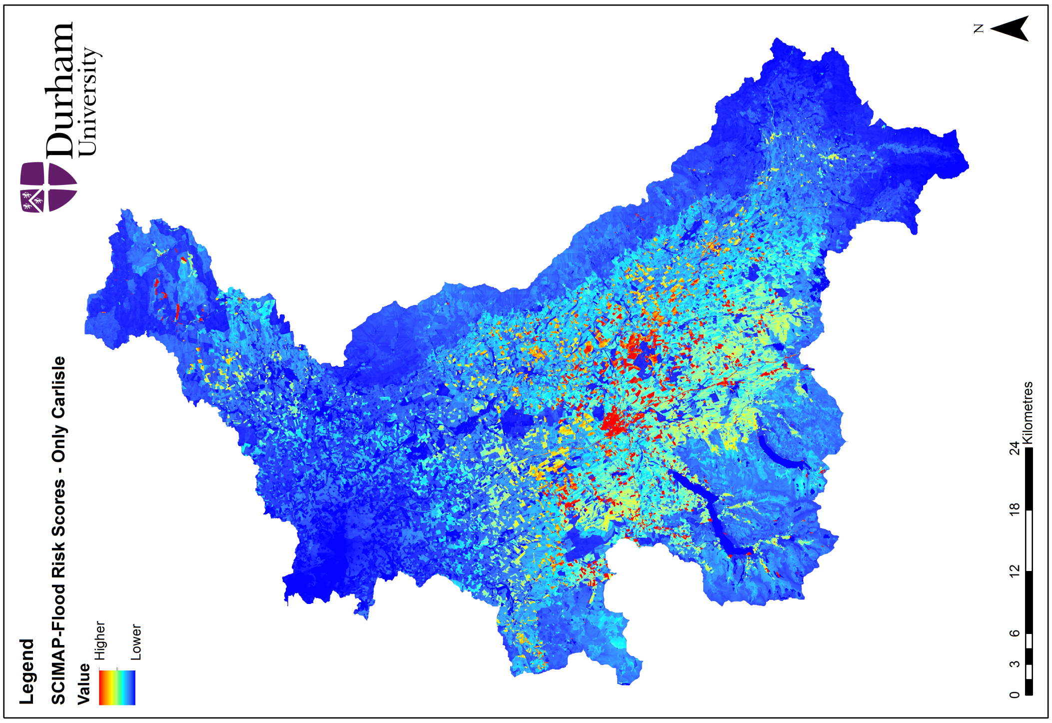


Figure 11 SCIMAP-Flood for the River Eden catchment for the single point of impact in Carlisle

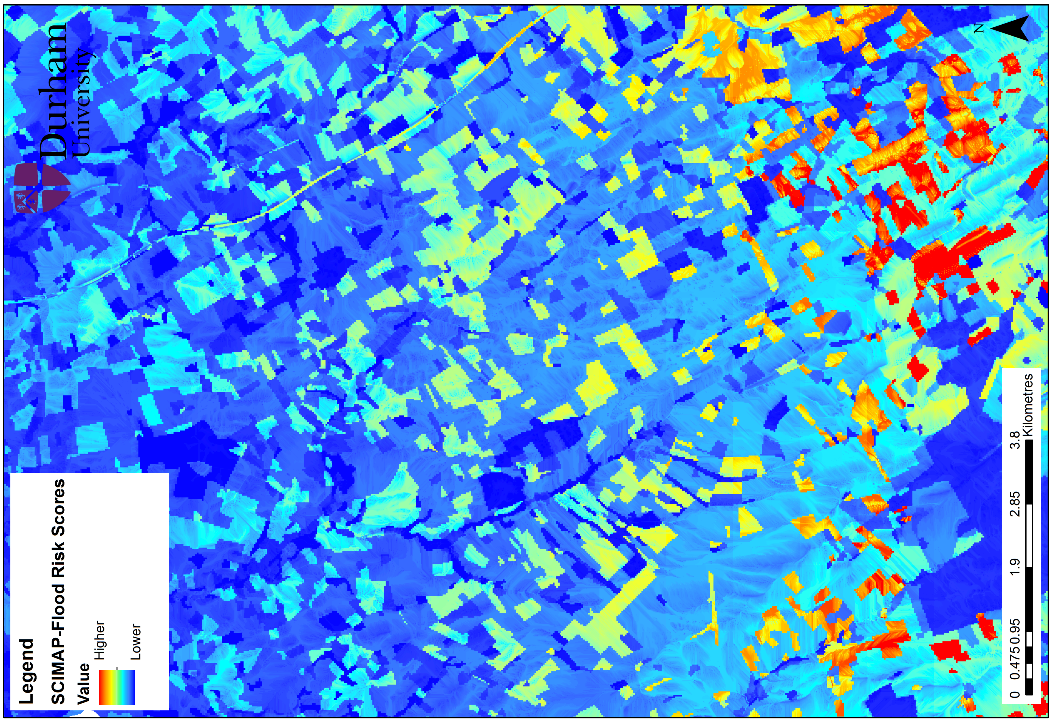


Figure 12 Detail of the field scale nature of SCIMAP-Flood for the River Roe catchment

Sub-Catchment Modelling Results from CRUM3

Model Performance assessment

Each of the 5014 model runs of the GLUE analysis were subject to performance testing through Nash-Sutcliffe and log Nash-Sutcliffe model performance statistics (Nash and Sutcliffe 1970). The CRUM3 model achieved a maximum Nash-Sutcliffe value of 0.69 and a log Nash-Sutcliffe value of 0.84. The maximum Absolute Flood Peak Ratio was 0.999 with 1.0 representing a perfect fit. These summary performance statistics show that the model is representing the catchment hydrological behavior well and can be used to test mitigation scenarios. The overall performance of the top 30 GLUE model runs is shown in Figure 13.

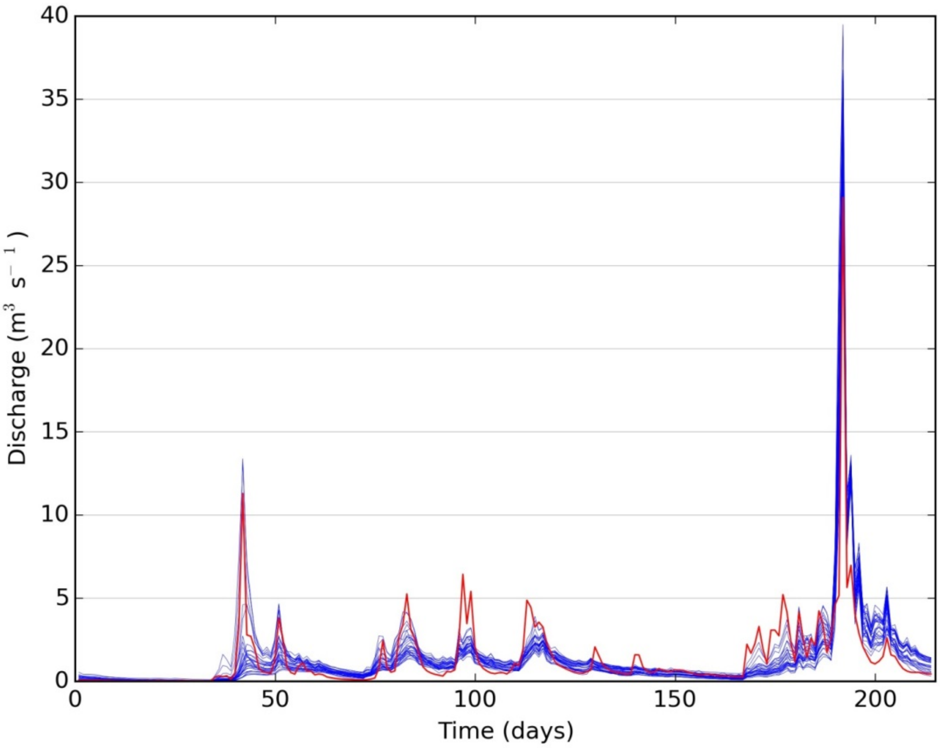


Figure 13 Average daily flow for the simulated time period up to and including the 2005 flood event (day 191). Red line is the daily observed data from the Environment Agency. Blue lines are the top 30 GLUE model runs.

Performance of Flood Management Measures

The assessment of land use management for flood risk reduction purposes was achieved by analysing the percentage change in the maximum river flow (MaxQ) at the location of the Environment Agency gauging station in Stockdalewath for each of the 30 behavioural model parameter sets.

Land cover targeted soil aeration results

The results for the land cover targeted soil aeration scenarios for the top 30 ranked model runs are shown in Figure 14. The greater the amount of catchment area assigned to soil aeration application the greater the reduction in MaxQ. Though unrealistic in their usage as a flood risk reduction due to the required area to be aerated and the unlikeliness that the entire catchment will be compacted, the use of soil aeration has a significant impact on the MaxQ in the Roe catchment.

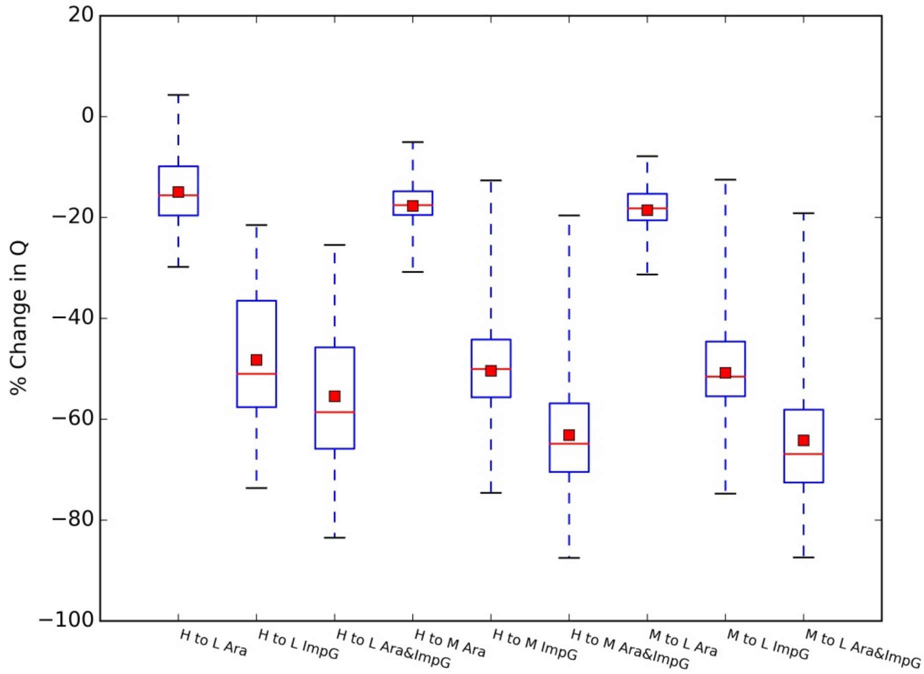


Figure 14 The MaxQ percentage change using the land cover targeted soil aeration scenarios. 'H' refers to heavy compaction levels, 'M' to medium compaction levels and 'L' to light compaction levels. 'Ara' is the arable land cover category and 'ImpG' is the improved grassland land cover category.

Applying soil aeration techniques until the soil is at the light compaction level to an assumed existing heavy compaction level across both the improved grassland and arable land cover in the catchment returned a mean and median reduction in MaxQ of -55.47% and -58.62%. Achieving a medium compaction level from an existing high compaction level had a mean and median reduction in MaxQ of -63.13% and -64.86% and moving from a medium compaction level to a light compaction level had a mean MaxQ reduction of -64.19% and median of -66.89%.

Aerating the arable land in the catchment had a mean reduction in MaxQ of -14.93% going from a heavy to light soil compaction level, -17.70% from a heavy to medium soil compaction level and -18.53% from a medium to light soil compaction level. Complete soil aeration to the catchment improved grassland land cover had a mean reduction in MaxQ of -48.26% going from a heavy to light soil compaction level, -50.38% from a heavy to medium soil compaction level and -50.79% from a medium to light soil compaction level.

The assumed heavy compaction to light compaction level scenarios has, perhaps unexpectedly, the smallest impact on MaxQ reduction. This can be attributed to the soil parameter relationship and the increased difference between the original and aerated soil parameters in comparison to the other two scenario sets. The greatly increased porosity and infiltration capacity of the soil could result in throughflow moving slightly faster through the dynamic layer and hence the lesser reduction in MaxQ.

Large woody debris dams scenario results

The results for simulating LWD dams using the three maximum discharge percentages are shown in Figure 15 (-2.2% reduction in maximum discharge), Figure 16 (-25%) and Figure 17 (-40%). For all three scenario sets the implementation of LWD dams in both Strahler 1 and Strahler 2 channel reaches results in an increase in mean and median MaxQ. This is potentially due to the flow restriction prolonging the maximum discharge moving through to the downstream cell where the LWD dams are placed and the cumulative effect at Stockdalewath of prolonged, but restricted, maximum discharge in addition to the unwooded channels is an increase in MaxQ. All three scenario sets with LWD dams on Stahler 3 channels had a reduction in MaxQ; the -2.2% scenario had a mean MaxQ reduction of -1.06% and a median MaxQ reduction of -1.09%, the -25% scenario had a mean reduction of -2.37% and median reduction of -2.91% and the -40% scenario had a mean reduction of -4.33% and a median of -4.61%.

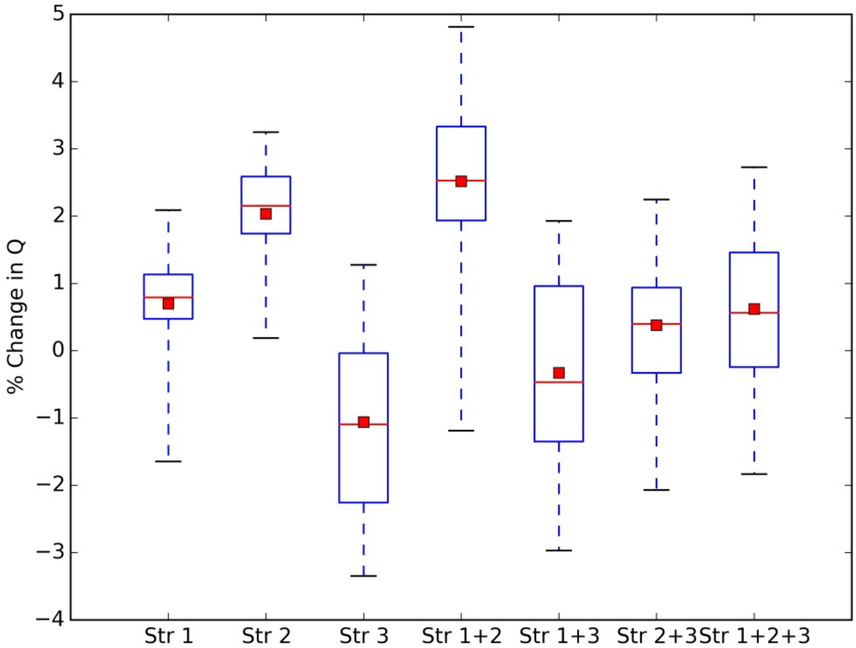


Figure 15 LWD dam scenarios for the Strahler number combinations using the -2.2% maximum discharge reduction from Wenzel et al. (2014).

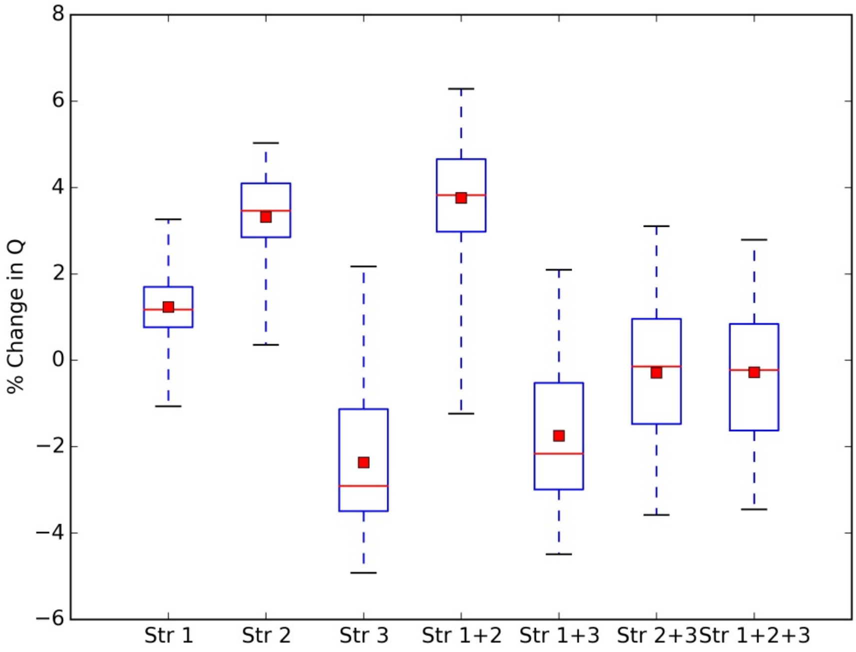


Figure 16 LWD dam scenarios for the Strahler number combinations using the -25% maximum discharge reduction from Wenzel et al. (2014).

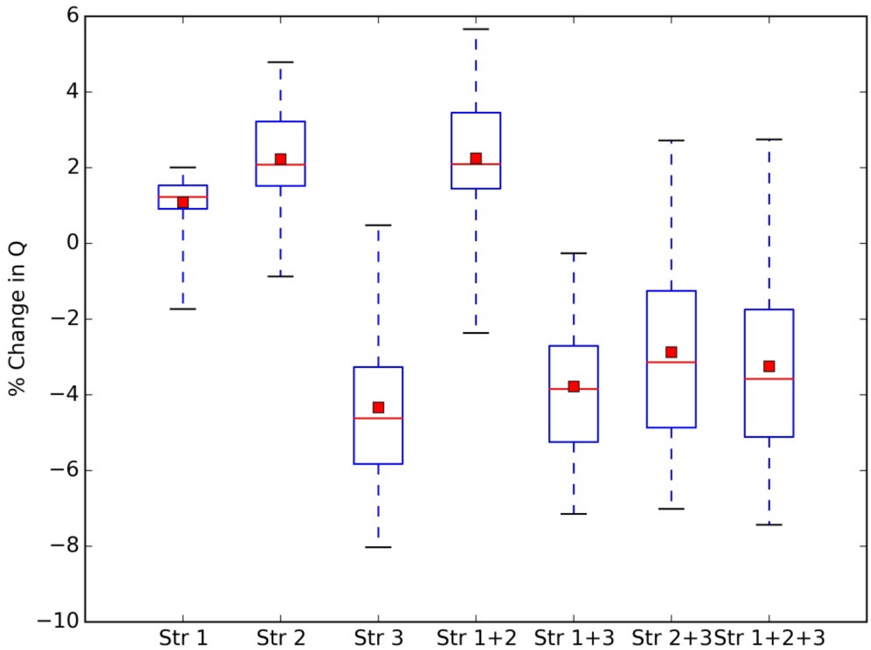


Figure 17 LWD dam scenarios for the Strahler number combinations using the -40% maximum discharge reduction from Wenzel et al. (2014).

The use of combinations of Strahler numbers to increase the catchment area under the influence of LWD dams failed to produce an increase in the reduction in MaxQ when compared to the Strahler 3 only LWD dam scenarios. The collective mean and median increase on MaxQ from the Strahler 1 and, in particular, Strahler 2 LWD dams decreased the effectiveness of the Strahler 3 LWD dams at reducing MaxQ. This is highlighted using the difference in mean MaxQ reduction in the Strahler 1 and 3 and Strahler 2 and 3 scenarios; for the -25% scenario the Strahler 1 and 3 scenario had a mean MaxQ reduction of -1.75% and the Strahler 2 and 3 scenario had a -0.28% reduction and the 40% scenario had a corresponding mean MaxQ reduction of -3.78% and -2.87%.

The LWD dam scenario results for all three maximum flow reduction percentages suggest that for the greatest impact on MaxQ (and thus for flood risk reduction) LWD dams should be concentrated on wooded channels with a Strahler value of 3 for the Roe catchment. It must be noted that creation of an average maximum discharge for each Strahler value to maximise the simplicity of the scenarios had a potentially significant impact on the MaxQ reduction.

Summary and Conclusions

SCIMAP-Flood offers a rapid assessment tool for determining the locations within large catchments where natural flood risk management techniques designed to slow the flow of water could be implemented. The example application of the prototype SCIMAP-Flood tool to the River Eden catchment shows that there are opportunities for actions within the mid-section of the catchment, more opportunities in the wetter southern side of the valley. The use of multiple points of impact results in the majority of the identified sites being located in the upper part of the catchment since mitigation works in these locations have the capability to benefit multiple downstream communities. This rapid assessment tool could be developed further to be user accessible through a web-interface along similar lines to the my.scimap web based tool (http://my.scimap.org.uk/).

The application of the CRUM3 catchment hydrological model to River Roe sub-catchment of the River Eden shows that this tool can be applied to simulate natural flood management techniques and interventions and quantify the corresponding impact on catchment hydrology in a rural catchment. The hydrological model was used to assess the effectiveness of a variety of flood risk reduction scenarios in the Row Beck catchment; these scenarios included spatially targeted land cover change to attenuate overland flow, soil aeration to mitigate soil compaction issues commonly associated with rural catchments and woody debris dams to slow the delivery of water downstream. It was established through the research that a significant proportion of land has to be acted upon to have a noticeable reduction in the maximum discharge produced during a flood event; as a consequence of this large scale soil aeration to keep soil compaction to low levels throughout the catchment is arguably the most useful natural flood management measure. Soil aeration produced the greatest reduction in maximum discharge of up to -64.20% and had a positive impact on the catchment low flow regime; additionally, would provide a benefit to the agricultural productivity that is essential for implementation in a rural catchment.

The combination of the rapid risk and opportunity mapping with SCIMAP-Flood and the detailed hydrological modelling with CRUM3 provides a powerful toolkit to spatially target and assess natural flood risk management schemes. SCIMAP-Flood enables the rapid and cost effective identification of sub-catchments and the areas within those catchments that are most likely to be contributing to the flood peak at the defined point of interest, such as Carlisle or Appleby-in-Westmoreland. CRUM3 can then be implemented to test NFM schemes and provide quantitative predictions of the change in flood peak magnitude required for project funding.

References

Beven, K. and Binley, A., 1992. The future of distributed models: Model calibration and predictive uncertainty. *Hydrological Processes*, 6, pp.279–298.

Beven, K.J. and Kirkby, M.J. 1979. A Physically Based, Variable Contributing Area Model of Basin Hydrology; *Hydrological Sciences Bulletin* **24**, 43-6

Boardman, J., 2003. Soil erosion and flooding on the eastern South Downs, southern England, 1976-2001. *Transactions of the Institute of British Geographers*, 28(2), pp.176–196.

Environment Agency, 2011. *Runoff Attenuation Features: A guide for all those working in catchment management*, Newcastle, UK.

Forestry Commission Wales, 2007. *Evaluation of Large Woody Debris in Watercourses*, Forestry Commission.

Heathwaite, A.L., Quinn, P.F. & Hewett, C.J.M., 2005. Modelling and managing critical source areas of diffuse pollution from agricultural land using flow connectivity simulation. *Journal of Hydrology*, 304(1), pp.446–461.

Lane S N, Reaney S M and Heathwaite A L 2009: Representation of landscape hydrological connectivity using a topographically-driven surface flow index; Water Resources Research, **45**, W08423doi:10.1029/2008WR007336

Lane S N, Reaney S M and Heathwaite A L 2009: Representation of landscape hydrological connectivity using a topographically-driven surface flow index; Water Resources Research, **45**, W08423doi:10.1029/2008WR007336

Lane, S.N., Brookes, C.J., Kirkby, M.J. and Holden, J. 2004. A network-index based version of TOPMODEL for use with high-resolution digital topographic data. *Hydrological Processes,* **18**, 191-201.

Lane, S.N., Odoni, N., Whatmore, S.J., Ward, N. & Bradley, S., 2011. Doing flood risk science differently : an experiment in radical scientific method. *Transactions of the Institute of British Geographers*, 36(1), pp.15–36.

Milledge D. G., Lane S. N., Heathwaite A. L. and **Reaney S. M.** 2012: A Monte Carlo approach to the inverse problem of diffuse pollution risk in agricultural catchments; *Science of the Total Environment* **433**, 434–449 http://dx.doi.org/10.1016/j.scitotenv.2012.06.047

Nash, J. & Sutcliffe, J., 1970. River flow forecasting through conceptual models part I - A discussion of principles. *Journal of Hydrology*, 10(3), pp.282–290.

Nisbet, T.R., Marrington, S., Thomas, H., Broadmeadow, S. & Valatin, G., 2011. *Defra FCERM Multi-objective Flood Management Demonstration project*, London.

O'Connell, P.E., Ewen, J., O'Donnell, G. & Quinn, P., 2007. Is there a link between agricultural land-use management and flooding? *Hydrology and Earth System Sciences*, 11(1), pp.96–107.

Pattinson, I., 2010. *Rural Land Management Impacts on Catchment Scale Flood Risk*. Durham University. http://etheses.dur.ac.uk/531/

Pearson C. J. 2016: Modelling the potential impact of spatially targeted natural flood management at the landscape scale for a rural UK catchment. Masters thesis, Durham University. http://etheses.dur.ac.uk/11734/

Posthumus, H., Hewett, C.J.M., Morris, J. & Quinn, P.F., 2008. Agricultural land use and flood risk management: Engaging with stakeholders in North Yorkshire. *Agricultural Water Management*, 95(7), pp.787–798.

Quinn, P., O'Donnell, G., Nicholson, A., Wilkinson, M., Owen, G., Jonczyk, J., Barber, N., Hardwick, M. & Davies, G., 2013. *Potential Use of Runoff Attenuation Features in Small Rural Catchments for Flood Mitigation*,

Reaney S M**,** Bracken (nee Bull) L J and Kirkby M J 2007: The use of the Connectivity of Runoff Model (CRUM) to investigate the Influence of Storm Characteristics on Runoff Generation and Connectivity in Semi-Arid Areas; *Hydrological Processes* **21** 894 – 906

Reaney S. M., Lane S. N., Heathwaite A. L. and Dugdale L. J.2011: Risk-based modelling of diffuse land use impacts from rural landscapes upon salmonid fry abundance; Ecological Modelling Volume 222, Issue 4, 24 February 2011, Pages 1016-1029doi:10.1016/j.ecolmodel.2010.08.022

Rigon et al. 2016: The geomorphological unit hydrograph from a historical-critical perspective; ESPL **41** 27-37

Smith, K.A., 2011. *Evaluation of land management impacts on low flows in northern England*. Durham University.

Tanguy, M.; Dixon, H.; Prosdocimi, I.; Morris, D. G.; Keller, V. D. J. (2015). Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890-2014) [CEH-GEAR]. NERC Environmental Information Data Centre.http://doi.org/10.5285/f2856ee8-da6e-4b67-bedb-590520c77b3c

Wilkinson, M.E., Quinn, P.F. & Welton, P., 2010. Runoff management during the September 2008 floods in the Belford catchment, Northumberland. *Journal of Flood Risk Management*, 3(4), pp.285–295.