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Spatial targeting of nature-based solutions for flood risk management within river catchments

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Abstract

A wide range of nature-based solutions for flood hazard management work by storing and slowing flow within catchments, and therefore, there is a need to identify the optimal locations for implementing these solutions. This paper presents a relative scoring-based mapping of the likely locations that contribute to the flood peak. Targeting flow reduction and attenuating mitigation actions in these locations can be an effective way to reduce flood damages at impact points downstream. The presented tool, SCIMAP-Flood, uses information on land cover, hydrological connectivity, flood generating rainfall patterns and hydrological travel time distributions to impacted communities to find the potential source areas of flood waters. The importance of each location in the catchment is weighted based on its contribution to the flood hazard at each of the downstream impact points. In the example application, SCIMAP-Flood is applied at a 5-m grid resolution for the River Eden catchment, Cumbria, England, to provide sub-field scale information at the landscape extent. Therefore, the tool can identify sub-catchments where more detailed work can test different mitigation measures.

KEYWORDS

flood hazard, landscape, mapping, natural flood risk management, nature-based solutions, spatial targeting

1 | INTRODUCTION

Recent changes in the approach to flood risk management have shifted the focus from hard engineered mitigation at the impact point to a combined system that includes managing flood waters' sources and pathways using nature-based solutions (NBS) (Pitt, 2007) with Natural Flood Risk Management (NFM) (Dadson et al., 2017) being a subset of NBS. There are global examples of the use of NBS for the management of flood hazards. In the United Kingdom, Wilkinson et al. (2010) and Lane et al. (2011) have applied NBS to catchments in northern England, Ferreira et al. (2020) studied NBS performance in central Portugal, Acreman et al. (2021) present a review of studies on the use of NBS in Africa and Chen et al. (2021) presented results from NBS application in Costa Rica. These studies have shown that there is great potential for nature-based solutions to be part of the flood management toolkit.

The mitigation methods used within NBS for flood hazard reduction include leaky debris dams within channels that slow the flood flow within lower order streams, distributed flood storage zones that capture flood waters from the main channel and changes to soil management that decrease the generation of flood forming rapid surface runoff. These NBS approaches work by slowing and storing the flood waters to reduce the flood peak, attenuating the flood. However, these actions can create problems if the peak is delayed such that it synchronises with a peak from another sub-catchment, potentially leading to an increase in flood risk downstream. To avoid this issue of unintended consequences, distributed modelling studies are undertaken to test the proposed NBS mitigation scheme; see Kumar et al. (2021) for a recent review of modelling approaches. Although these modelling approaches provide evidence for the effectiveness of the proposed scheme, four problems remain:

1. The viability of the NBS flood hazard mitigation scheme depends on the cost: benefit analysis (CBA) of scheme costs and potential damage reduction. The cost of detailed modelling needs to be added to the scheme's budget, affecting the CBA.
2. Although it is possible to apply simulation-based hydrological and hydraulic models at the landscape scale, compromises may be made in the spatial resolution and extent of the model, the number of rainfall events and the number of mitigation schemes that can be considered. However, the details of the effectiveness of mitigation actions on flood magnitudes are required to design and assess the schemes.
3. There is a need to generate the potential mitigation scenarios to be tested with the detailed modelling system, which are not provided by the modelling tools.
4. Since these NBS schemes are typically set within agricultural landscapes, there is a need to minimise impacts on farm businesses. Therefore, it is important that these features are implemented in the most effective locations to minimise agricultural productivity impacts.

Therefore, there is a need for simple, effective tools to spatially target NBS mitigation actions within catchments. To develop these tools, we need to consider how flood events develop within catchments and how this behaviour can be captured within a minimal information requirement style framework.

Flood waters and hazards are not produced in a uniform way across a landscape. Flood events are the product of integrated processes across a large catchment area, but the driving factors often occur at small spatial scales. Hence, the effectiveness of an NBS will be a function of its location within the catchment based on four factors: (1) local flood water generation, (2) hydrological connectivity to the river, (3) travel times to the impact point and (4) the spatial pattern of the rainfall event.

1.1 | Local flood water generation

How rainfall is converted into fast flows that generate fluvial flood events, such as overland flow, micropore flow or pipe flow, is controlled by the soil properties and these properties are strongly affected by the local land cover, use and management (Kirkby et al., 2002; Maetens et al., 2012). For example, soils with higher organic matter, macropores and higher permeability, such as those found under woodland land covers, tend to generate less rapid overland flow (Zimmermann et al., 2006). In contrast, soils with high livestock numbers or use of agricultural machinery tend to have higher compaction rates that limit infiltration (Hamza & Anderson, 2005) and may also have drainage pipes installed. Both factors can result in an increased rate of rapid runoff generation (Maetens et al., 2012). All these patterns are affected by the soil types within the catchment, but land use both correlates with the soil type and exerts a significant modifying influence upon the hydrological properties.

1.2 | Hydrological connectivity

The hydrological connectivity describes the ease with which water from one location in the landscape can move to another (Bracken et al., 2013; Bracken & Croke, 2007) and in the context of NBS for flood hazard reduction, this is the ease with which water can be moved from the location in the catchment where runoff is generated to the rivers or lakes. Therefore, hydrological connectivity is an essential part of understanding the water movement within storms that create flood events (Keesstra et al., 2018; Rogger et al., 2017). Within catchments, the factors that affect the strength of the hydrological connectivity include points in the landscape that disconnect hydrological flows (Reaney et al., 2011), trackways that increase the hydrological connectivity (Deasy et al., 2009). Therefore, to capture these connectivity patterns and topographic data with a ground resolution of five metres or less is required.

1.3 | Travel times

The topographic form of the catchment affects when water reaches an impact point. This relationship between the catchment form and the hydrological response has been modelled as by the instantaneous unit hydrography (Gupta et al., 1980; Jakeman et al., 1990) and as the Width Function-based Geomorphologic Instantaneous Unit Hydrograph (Hallema et al., 2016). By considering the distribution of flows path lengths within the catchment, the locations within the catchment with median flow path lengths are most likely to be contributing to the flood peak. Targeting NBS in these locations is expected to be beneficial in reducing the flood hazard as they will move water from the peak into the receding limb. NBS that slow the flow that are implemented in areas that contribute to the rising limb have the capacity to increase the flood hazard, and hence works in these areas should be avoided. Where there are multiple impact points within the catchment, such as settlements or key infrastructure, there are spatial distributions of travel times, and the median locations for one impact point may be on the rising limb part for another impact point. These catchment travel times, therefore, need careful consideration.

1.4 | Rainfall patterns

The types of storm events that have historically given rise to flood events have been shown to be related to specific circulation patterns within the regional climate (Pattison and Lane, 2012). Therefore, it is important to consider the flood generating rainfall patterns across the catchment when considering where flood waters are generated rather than the average conditions. These rainfall patterns can capture the effects of orographic rainfall related to the topography of the catchment.

Considering these four factors means that the calculated spatial targeting maps for NBS measures have the greatest chance of reducing flood risk over a range of possible future events. Due to differences in storm event characteristics, antecedent hydrological conditions and land management, the importance of each of these factors will vary between storm/flood events. Hence, there is a need to manage the hazard for a range of probable scenarios within an uncertainty framework. This paper presents a rapid broad-scale mapping method that identifies where to implement flow-slowing NBS measures within the catchment that are most likely to be effective under a range of possible future storms.

2 | METHODS

The approach taken with SCIMAP-Flood is to determine the suitability of a location for implementing natural flood risk mitigation measures based on the SCIMAP fine sediment source area mapping tool (Reaney et al., 2011) but expanded to capture the flood specific issues. The SCIMAP-Flood tool assigns relative scores 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 (Heathwaite et al., 2005), whereby there needs to be both a generation of flood waters and an active hydrological connection to the river channel. The source potential is determined as a function of travel times, local runoff generation potential, hydrological connectivity and rainfall pattern. The workflow of the processing of the datasets is shown in Figure 1.

2.1 | Example application catchment: The River Eden, United Kingdom

SCIMAP-Flood has been applied to the River Eden catchment in northwest England, Figure 1. This catchment has a history of flood events, with notable events occurring in 2005, 2015 and 2020, where significant flooding was experienced in Appleby-in-Westmoreland, Penrith, Carlisle and many other rural communities. The catchment covers 2288 km^2 and includes parts of the Lake District National Park and the Pennine hills. The land cover is mainly agricultural, with 73% of the catchment used for livestock on grasslands and 11% of the catchment used for arable production. The average rainfall depth is variable within the catchment, with a maximum rate of 3476 mm year^{-1} in the highlands and a minimum rate of 777 mm year^{-1} in the lowlands. The catchment bedrock is a mixture of volcanic rocks and sandstone, forming a

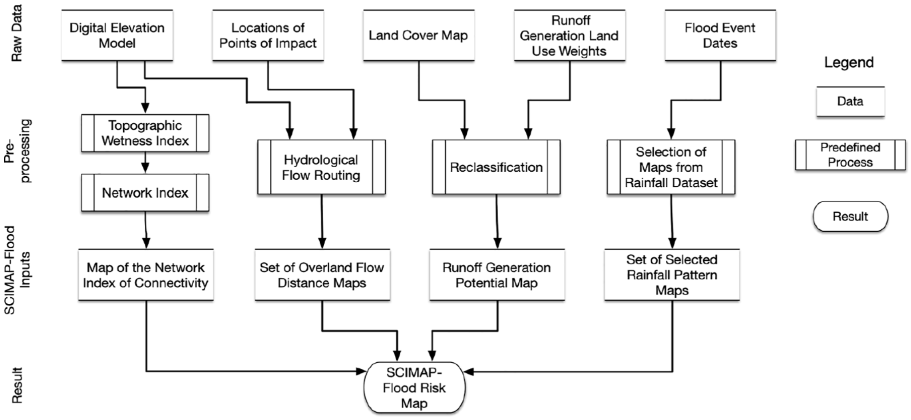

FIGURE 1 Flowchart of the processing workflow for SCIMAP-Flood

significant aquifer in the valley. The superficial deposits are glacial till which often creates a barrier between the surface hydrology and the groundwater. The main soil types are the Wick, Newbiggin, Malvern, Clifton and Winter Hill series.

These rural land uses, high rainfall, and surface hydrological pathways mean that the catchment is suitable for a range of nature-based solutions for flood risk reduction. A local environmental NGO, the Eden Rivers Trust, has implemented a range of mitigation schemes, including soil aeration to decrease surface runoff, riparian planting to create roughness and disconnect surface flows from the river and river restoration to reconnect rivers with their floodplain storage. This combination of physical suitability and active mitigation works makes the River Eden catchment a suitable demonstrator for the SCIMAP-Flood approach.

The data used in this application of SCIMAP-Flood consisted of:

- The 5 m NextMap digital terrain model dataset (Intermap Technologies, 2007).
- Land cover information from the CEH Land Cover Map 2007 (Morton et al., 2011).
- Rainfall patterns from the CEH GEAR dataset (Tanguy et al., 2015).

Both the land cover information and the rainfall patterns were resampled to 5 m using a nearest-nearest neighbour algorithm to match the DTM. This detailed assessment means that it is possible to give sub-field level assessments of flood water generation at the landscape spatial extent (Figure 2).

2.2 | Travel times

To keep with the minimal information requirement approach, this paper adopts a simplified version of the unit hydrograph approach by calculating the flow lengths within the catchment based on hydrological routing. These travel times were calculated with the DTM using the FD8 algorithm (Quinn et al., 1991) after the DTM had been preprocessed to remove sinks using the 'deepen drainage routes' algorithm in SAGA-GIS (Conrad et al., 2015). The area that may contribute to the flood peak has been defined by the median 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 median travel time. A separate travel time map is calculated for each impact point within the catchment.

2.3 | Local runoff generation

The rate of local runoff generation can be considered to be based on a combination of the land cover, land management, soil properties, geology and slope gradient. There are, however, several cross-correlations between these variables, which enable a simplification for the processes, which is acceptable for a relative minimum information requirement-based approach. The land cover has been taken as the dominant factor within this application since the other key factors co-vary with land cover. Depending on local conditions, it is possible to include the other variables in an explicit rather than implicit way within the SCIMAP-Flood framework. The spatial pattern of land cover has been based on a simplification of the CEH Land Cover Map 2007 (Morton et al., 2011), as described in Table 1. Each land cover has been assigned a score between zero and one based on its relative potential to generate runoff. These are subjective weightings based on the runoff generation potential of the different land covers within the catchment.

2.4 | Rainfall patterns

The rainfall patterns that have given rise to historical flood events within the River Eden catchment have been selected from the CEH Gridded Estimations of Areal Rainfall, GEAR, dataset (Tanguy et al., 2015). This dataset comprises daily rainfall estimates based on the observed rain gauges presented in a 1 km × 1 km 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 for the years 1964–2011. The stations used were Warwick Bridge (id 76002), Sheepmount (id 76007), Udford (id 76003), Temple Sowerby (id 76005) and Great Musgrave (id 76021). The date of the top five peak flows for each of these stations were selected, Table 2, and after duplicate storms affecting multiple flow gauges have been removed.

2.5 | Integration of factors

The different rainfall patterns, travel times and flood water generation potential are combined to give an integrated assessment of the locations most suitable for implementing mitigation measures. The flood hazard source potential (F) is determined by:

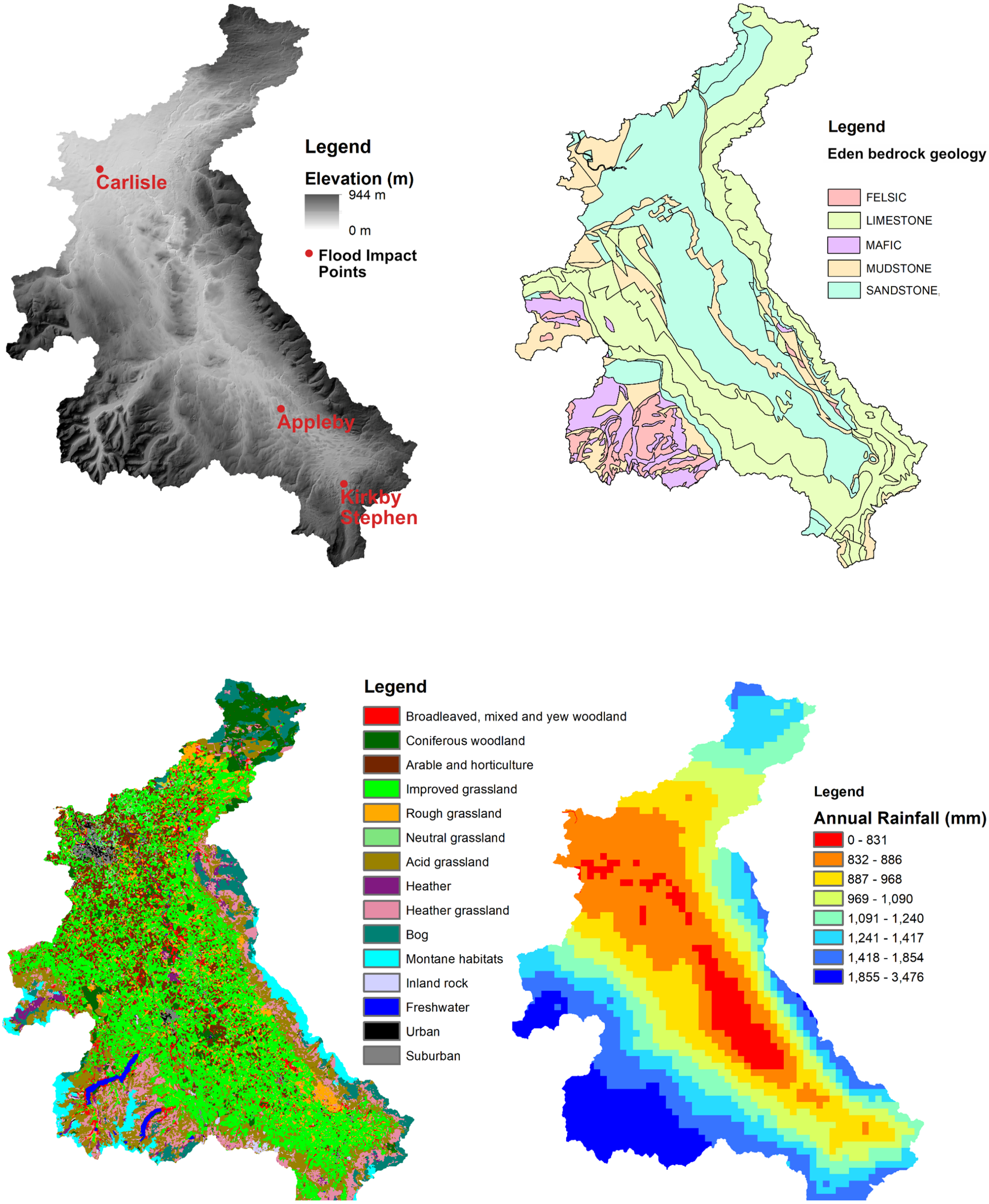

FIGURE 2 The topography (NextMap 5 m DTM dataset, Intermap Technologies, 2007) showing the flood impacts points used in the analysis, geology (British Geological Survey 1:625k dataset, contains British Geological Survey materials © UKRI 2022), land cover (CEH Land Cover Map 2007, Morton et al., 2011) and rainfall patterns (CEH GEAR dataset using the 1980–2010 mean, Tanguy et al., 2015) of the River Eden catchment

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

where rf is the rainfall map, tt is the travel time map, L is the land cover flood generation potential, R is the rainfall pattern, C is the hydrological connectivity, and T is the travel time factor. The F value is then normalised between zero and one. The uncertainty in the predictions is calculated as the coefficient of variation of the different factor combinations for each location.

TABLE 1 List of flood water generation weightings for different land covers within the River Eden catchment

Id	Land cover	Weight	Notes
1	Woodland	0.05	Woodland has been given a lower weight due to the high infiltration rates and lower saturation deficits within the soil
2	Arable	0.8	Arable has been assigned a high 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 higher weighting than unimproved grasslands due to the likely compaction of the soils by livestock and machinery, which often results in lower infiltration rates.
4	Unimproved grassland	0.15	Unimproved grassland has been given a weight midway between woodland and improved grass
5	Urban	1.0	Urban has been assigned a high weight due to the impervious surfaces and effective drainage that rapidly transfers water to the river channels.
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 mitigation measures, and hence water has been given a low value

TABLE 2 Historical flood events within the River Eden Catchment based on the CEH GEAR dataset

Date	Stage (m)	Flow (m^3/s)	Location	Date	Stage (m)	Flow (m^3/s)	Location
09/12/1964	2.499	300.1	Udford	01/02/1995	5.149	811.8	Warwick Bridge
09/12/1964	4.883	719.1	Warwick Bridge	20/02/1997	4.715	666.6	Warwick Bridge
23/03/1968	5.930	1103.9	Warwick Bridge	03/02/2004	2.705	230.3	Great Musgrave
24/03/1968	6.266	1200.0	Sheepmount	07/01/2005	2.887	276.8	Great Musgrave
24/03/1968	4.040	663.0	Temple Sowerby	08/01/2005	7.226	1516.4	Sheepmount
24/03/1968	2.560	313.7	Udford	08/01/2005	4.330	925.0	Temple Sowerby
04/01/1982	5.583	957.5	Sheepmount	08/01/2005	2.846	399.4	Udford
21/12/1985	3.788	484.1	Temple Sowerby	18/11/2009	2.748	240.7	Great Musgrave
21/12/1985	2.533	307.6	Udford	19/11/2009	2.908	417.4	Udford
21/12/1985	5.093	793.5	Warwick Bridge	20/11/2009	5.813	1029.3	Sheepmount
24/02/1991	3.730	448.7	Temple Sowerby	04/11/2010	2.792	251.7	Great Musgrave
31/01/1995	3.880	544.6	Temple Sowerby	08/12/2011	2.902	280.9	Great Musgrave
01/02/1995	5.568	952.8	Sheepmount				

3 | RESULTS

The travel time calculation approach has been implemented for three impact points within the catchment, Carlisle, Appleby-in-Westmoreland, and Kirkby Stephen, Figure 3. The results in Figure 3 show how the areas highlighted in blue are most likely to contribute to the flood peak at the different impact points, assuming uniform runoff generation. For each flood impact point, the source areas of the flood peak water change

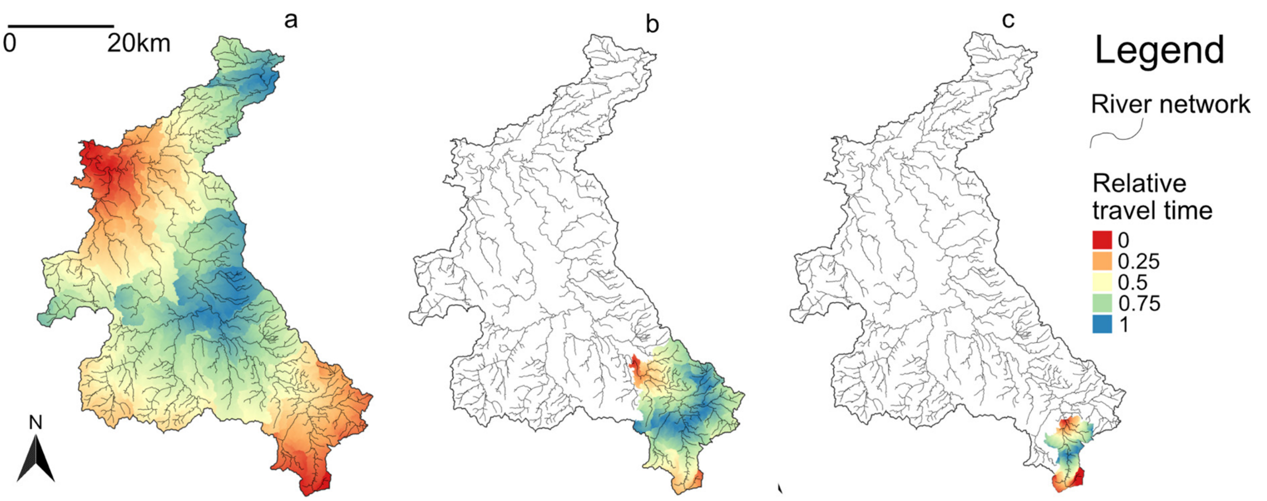

FIGURE 3 Relative travel time distributions for (a) Carlisle, (b) Appleby-in-Westmoreland and (c) Kirkby Stephen. Legend units are in relative travel time within the catchment. The travel time distributions are based on the overland flow distances across the catchment from each grid cell to the impact point and show the potential for flow concentration from the areas coloured in red, to form flood peaks. Rivers lines are from the OS Open Rivers dataset

significantly within the catchment with an overlap in the predicted locations of the flood peak waters. For example, flood water peak locations for Appleby are rising limb of the flood hydrograph at Kirkby Steven. Slowing flow at these locations could therefore increase the flood hazard at Kirkby Stephen. The reclassified land cover map for the runoff generation and the hydrological connectivity predictions are shown in Figure 4. The maps in Figure 4a,b show how the strength of the hydrological connectivity varies both across the catchment and within fields. It is predicted that there will be stronger hydrological connectivity in the lowland part of the catchment, south of Carlisle, as shown in the blue tones. It is predicted that there is lower strength hydrological connectivity in the uplands, such as in the southwest and southeast of the catchment. The maps in Figure 4c,d show that the runoff generation potential is greatest in the lowland sections of the catchment, which are dominated by improved grasslands and arable land covers. The uplands, which are dominated by moorland and woodlands, are predicted to have lower runoff generation potential. As with the hydrological connectivity, there are variations in the runoff generation potential at the catchment and local field scale. For the rainfall patterns, a set of 13 storm patterns were selected, and Table 2 lists the events and Figure 5 shows the range of different rainfall patterns. The range of rainfall patterns shows that for flood generating storm events, the greatest depths are often recorded in the southwest and southern highlands of the catchment.

The results of the SCIMAP-Flood analysis consist of four maps of the River Eden catchment showing the mean and Coefficient of Variation for all impact points and the case of a single impact point in Carlisle. The dataset is available in Reaney (2021). Figure 6a shows the predicted relative pattern of flood water generation for all impact points (Carlisle, Appleby-in-Westmoreland and Kirkby Steven). The relative flood water source scores are shown with the colour hue, and their associated uncertainty is shown by the colour saturation, such that saturated red is the highest source score with the greatest certainty and desaturated red represents a high score but with low certainty. The map can be contrasted with the results for a single impact point at Carlisle, Figure 6b. The consideration of the multiple impact points weights the key source areas into the upper River Eden catchment since these locations have the potential to benefit all three impact points. The rainfall patterns are reflected in the focusing of the flood water generation potential in the southern section of the catchment. There are also large areas of connected improved grassland and areas that are also predicted to be important for generating flood waters in this part of the catchment. The land cover weights represent flood water generation, focus the results on the urban areas due to their high runoff and connectivity. Figure 6c shows the detail of the field-scale predictions, which allow for both individual fields and pathways within fields to be targeted for the implementation of mitigation features.

4 | DISCUSSION

One of the issues that face all nature-based solutions to flood risk reduction is the potential for unintended

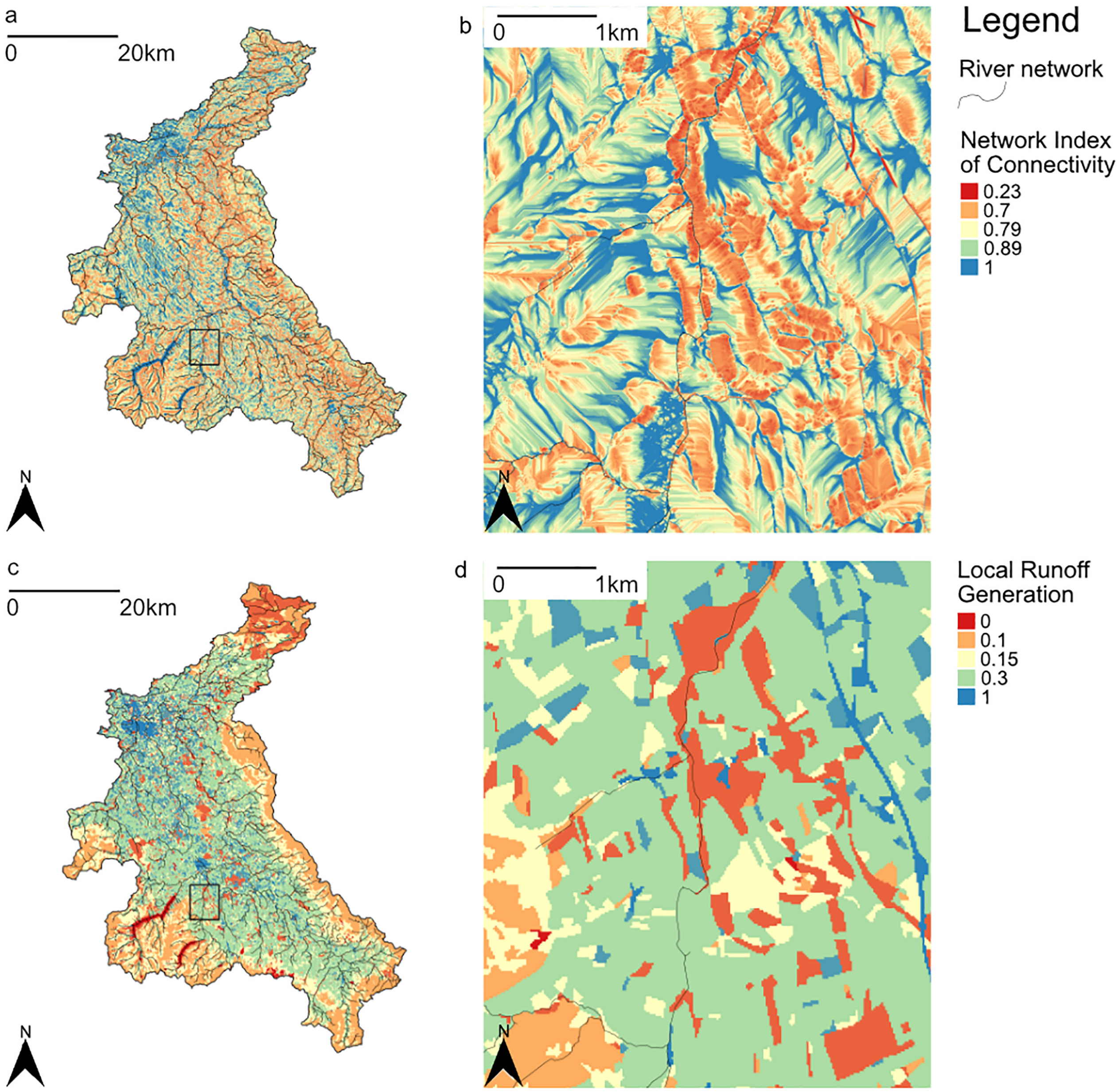

FIGURE 4 (a) Land cover based flood water generation potential weights for the River Eden Catchment based on the values in Table 1 showing how the flood water generation potential varies across the landscape and (b) detail of the runoff generation potential for a 5 km by 11 km area showing how flood water generation potential varies on a field by field basis. (c) Relative hydrological connectivity for the River Eden catchment based on the Network Index (Lane et al. 2004, 2009) and (d) detail of the hydrological connectivity patterns. A value of 1 represents the most connected areas, and zero represents the least connected areas

consequences. There is the potential for the slowed flow from one sub-catchment to synchronise with the flow from another, leading to an increased flood peak in certain parts of the catchment. In SCIMAP-Flood, the areas predicted to be beneficial to one impact point but detrimental to another can be identified by considering the difference between score maps for different impact points. Therefore, schemes proposed in these locations can be subjected to a greater level of scrutiny in the planning process. The local flood risk management authority's job is to work with the local community and stakeholders to balance the local versus catchment benefits of a large-scale scheme. The approach presented in this paper will enable these discussions to have a numerical foundation and to allow for an agreed common basis.

The balance of local versus catchment benefits is expressed within SCIMAP-Flood through the potential for weightings to be given to each impact point. In this

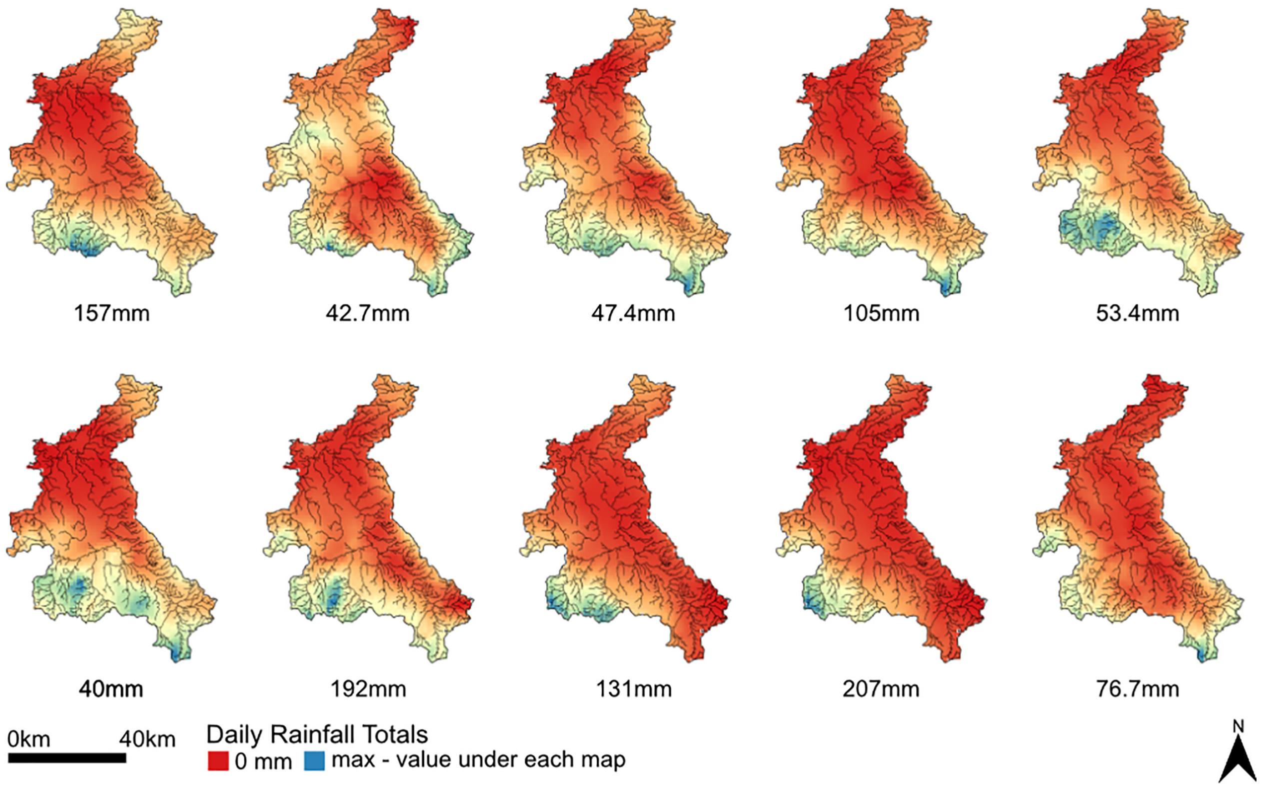

FIGURE 5 Example different daily rainfall patterns based on CEH GEAR 1 km rainfall data for rainstorms associated with flood flows within the River Eden catchment. Legend units are in mm day^{-1}, and the maximum daily rainfall is shown under each map

application, three impact points were considered, each of which were towns or a city, and they were implicitly equally weighted. These weights can be refined based on impact criteria, such as the number of people affected, the potential economic value of the flood damages or a measure based on the social vulnerability of the impacted people. The social vulnerability can be quantified using an approach such as the social flood vulnerability index (Cutter et al., 2003). The impact points do not have to only be communities at risk; they can also be key infrastructure, such as hospitals or transport links where a flood event may break the connectivity between a population and key services. These pieces of infrastructure give benefits to the wider catchment community, and hence there is a potential for trading a possible flood risk increase at the local community scale for a risk reduction at the key infrastructure locations. The acceptability of this trade will depend on the local attitudes of the community and the use of these services.

With an implementation of a landscape-based flood hazard reduction scheme, the timescales of the effectiveness of the different mitigation options need to be accounted for, and the interim states of the system need to be considered to ensure that the flood hazard is not temporarily increased whilst other measures mature. For example, the implementation of leaky dams within river systems can effectively slow the flow at that location as soon as they are built, but their performance will degrade over time due to both the silting up of the features and the failure of the wooden structure. However, land cover change, such as from grassland to woodland, will take many years to mature to the point that the woodland provides its complete set of flood-mitigating services. These changes in the flood risk reduction feature's effectiveness are also played out against the backdrop of the projected climate change over this century. The projected future climates may change the number of different atmospheric circulation types and the distribution of storm rainfall patterns (Lowe et al., 2018). Therefore, the schemes need to be effective under both the current and potential future climates. The rapid calculation of the presented approach means that this interplay of timescales can be investigated by considering a wide range of system configurations as the flood hazard reduction system matures over time to determine the locations that are effective under the broadest set of possible futures.

There are several issues and assumptions related to the data sets that drive SCIMAP-Flood, focused on the digital terrain model and land cover information. Terrain analysis-based systems are highly dependent on the quality of the input data and how this information is processed. Within SCIMAP-Flood, the terrain

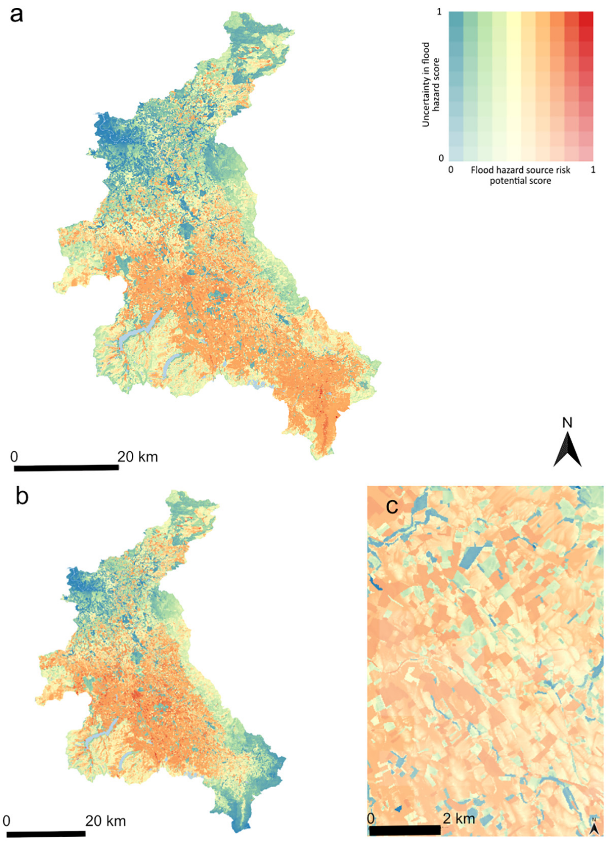

FIGURE 6 (a) SCIMAP-Flood for the River Eden catchment for all impact points; (b) SCIMAP-Flood for the River Eden catchment for the single impact point in Carlisle; (c) detail of the field-scale predictions from SCIMAP-Flood. The legend shows both the potential for a nature-based solution to slow and store flood water at a location to be successful with the colour and the certainty of the calculation, shown with the saturation. Hence, saturated red areas are the most certain that they will reduce flood hazards to the impact points across a range of storm events

information is used to calculate the flow directions, routing and accumulated travel time distributions and for the calculation of the hydrological connectivity. The flow routing within landscapes requires high-quality datasets since lower quality DEMs can route water in the wrong direction and have insufficient detail for the connectivity calculations. The NextMap 5 m DTM product was used for this application, and a range of other global products could also be used. The land cover information used for this study was from 2007 and hence represented a snapshot in time. Over the lifespan of mitigation measures, there will be changes in the land cover from crop rotations in agricultural areas and large-scale land cover changes due to drivers, including urbanisation and changing demands for certain agricultural products. This changing land use pattern can alter the spatial distribution of key flood water source areas from across the catchment. This application uses daily rainfall totals and hence does not consider the potential impacts from the storm front moving across the catchment and impacting the timing of runoff generation. This effect is likely to have more impact on larger catchments (Perez et al., 2021), where the movement of storms coincides with flow direction within the catchment, meaning flood waters are generated as the upstream flood peak passes (Doswell et al., 1996).

This application's flood water generation land cover weights were based on a logical, but subjective, set of values based on the land cover and its associated management. This part of the approach could be developed further by using the SCIMAP-Fitted method (Milledge et al., 2012; Reaney et al., 2011). This approach considers the observed pattern of flood peaks within a catchment and uses this spatial information to calculate the relative weights for the diffuse land covers or soil types.

Although the sample application was to the River Eden catchment in northern England, the approach has much broader applicability. The SCIMAP-Flood approach can be applied in any catchment where the runoff generation is affected by land cover, the topographic routing affects the flow concentration, and the rainfall pattern is non-uniform. This set of criteria is matched by many catchments worldwide. Within SCIMAP-Flood's current structure, the approach can be applied to any catchment where the water routing through the soil is lateral rather than vertical. These areas include surface water catchments in temperate and tropical environments. SCIMAP-Flood should be considered an approach that can be adapted to local conditions rather than a fixed model. Future work will consider how the approach can be applied in mountainous catchments in the Himalayas.

It has been documented that the nature-based solutions for flood hazard reduction can have many co-benefits, including improved water quality, increased biodiversity, increased natural pest control and greater amenity value for the local and visiting population (Pagano et al., 2019). The required spatial targeting of the measures means that certain communities will profit from the co-benefits and others will not. This uneven spread of benefits within the catchment raises questions about the equitable share of costs, impacts and benefits of flood schemes between the different parts of the catchment community. A second key community-related point relates to the potential issues associated with the assignment of the blame due to the misinterpretation of the maps. The SCIMAP-Flood approach aims to predict the origin, on average, of the water that contributed to a flood peak at an impact point. The maps should not be used to relate damage at a property to an individual action or location in the catchment.

5 | CONCLUSIONS

SCIMAP-Flood offers a rapid assessment tool for determining the locations within large catchments where nature-based solutions (NBS), designed to slow the flow of water for flood risk management, could be best implemented. The example application of the SCIMAP-Flood tool to the River Eden catchment shows opportunities for actions within the mid-section of the catchment, more opportunities in the southern side of the valley where the rainfall rates are often higher during flood causing storm events. The use of multiple flood impact points results in the majority of the identified sites being located in the upper part of the catchment since mitigation works in these locations has the potential to benefit multiple downstream communities.

The rapid relative scoring and opportunity mapping with SCIMAP-Flood provides a powerful toolkit component 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 towns or critical infrastructure. There is potential to apply the approach to other temperate and tropical catchments where the topography is the key control on the flood water routing.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Durham Research Data Collections at http://doi.org/10.15128/r1zs25x8480.

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