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MODELLING THE POTENTIAL FOR SPATIALLY DISTRIBUTED, NATURAL FLOOD-RISK MANAGEMENT TECHNIQUES TO MITIGATE FLOOD RISK AT THE CATCHMENT SCALE FOR A UK AGRICULTURAL CATCHMENT

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MSc by research

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Abstract

The impact of flooding throughout the UK is significant and the financial burden felt by individuals, communities and the government. Many flood alleviation schemes are delivered using hard-engineered approaches that can provide high standards of protection, but do not address the root cause of flooding. Delivering civil engineering schemes cannot always be justified using the current cost-benefit criteria or due to difficulties of in working within a settlement. This justifies the need to investigate sustainable, lower-cost initiatives that can be delivered more holistically and remotely from the receptor settlement. Natural Flood-Risk Management (NFM) is an area of great interest that has had several comprehensive reviews and a Defra release of £15 million in flood and coastal erosion risk management research and development funding. The aim of NFM is to work with natural hydrological processes and restore the natural water holding capacity of catchments. Currently, there is a lack of evidence on the benefits of this approach and whether or not they can be delivered efficiently to the same standard of protection for the same design life.

This research thesis used two complementary approaches to assessing NFM potential: (1) rapid connectivity risk mapping assessment (SCIMAP-Flood); and (2) detailed, physically based, fully spatially distributed simulation of catchment hydrology (CRUM3). These methods have been combined to provide a powerful toolkit to effectively target mitigation of flood risk and to simulate potential impact on flood peak through a variety of NFM interventions. These methods were applied to the study area (Tutta Beck), a 7.06km^2 agricultural catchment that flooded twice in 2012.

A variety of flood mitigation strategies were investigated in the Tutta Beck catchment, including spatially distributed land cover change to intercept and resist overland flow, woody debris dams to slow the flow of water through the channel network and spatially targeted depressions to attenuate overland flow. It was established for this catchment that the most effective technique for reducing peak discharge was the use of in channel large woody debris spatially targeted using SCIMAP-Flood, particularly when combined with spatially distributed attenuation.

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Chapter 1   Introduction

1.1   Introduction

Across England, approximately 5 million properties (1 in 6) are at risk of flooding: 2.4 million from fluvial/tidal sources and 3 million from pluvial sources (Defra & Environment Agency, 2014). During the winter of 2015–2016, storms Desmond, Eva and Frank caused widespread flooding throughout the UK, with December being the wettest December since records began. These storms caused flooding to 13,000 households and 4,000 businesses, with 14 catchments experiencing their highest recorded river flow since records began (Curtin, 2016). Lack of storage and slowing of water in catchments were cited as contributors to flooding (Department for Communities and Local Government, 2016), as was the last line of defence approach to flood defences nationwide.

Flood alleviation schemes (FAS) attract funding based on a cost-benefit analysis, the most significant claimable benefit being reducing risk to properties (Outcome Measure 2/OM2). However, in rural areas, fewer properties mean it is difficult to demonstrate sufficient properties will benefit to cover the cost of a tradition FAS. In such cases, low-cost interventions with additional benefits, such as Natural Flood-Risk Management (NFM) and Sustainable Drainage Systems (SuDS), are being considered. This research refers to all options as 'NFM' structures but, as mentioned in subsequent sections, in cases in which they can be optimised/substituted for a SuDS or diffuse pollution structure/technique this will not be excluded.

NFM seeks to increase or reintroduce a catchment's natural storage capacity for flood risk reduction purposes. NFM is poorly defined; only recently have organisations such as the Scottish Environmental Protection Agency (SEPA) (SEPA, 2015) and the Environment Agency (EA) (Environment Agency, 2017) released NFM reviews and guidance, a significant finding being the need for further research. Prompting the release of £15 million pounds for Research and Development funding for NFM projects nationwide. There are many questions with regard to the effectiveness of and opportunities for NFM (Dadson et al., 2017) including whether, fundamentally, NFM is a technique, toolkit or a delivery approach (Fraser et al., 2017a; Fraser & Reaney, 2018).

Traditionally, the recording of floods was dominated by overflowing watercourses having an impact on a receptor (Kozlowski, 1984; Meurant, 2012), resulting in a strategy focused on protecting the receptor. Recent events demonstrate that protection alone is not sustainable (Pitt, 2008; SEPA, 2015) with the emphasis moving to catchment-wide water management as outlined in catchment management plans (Environment Agency, 2009a).

The impact of flooding on communities and the desire for those communities to have their voices heard has led to an increase in community engagement within the flood risk sector (Defra & Environment Agency, 2005; Nisbet et al., 2011; Daly et al., 2015; Bracken et al., 2016; Cook et al., 2016; Cobbing, 2017). There has been a significant shift in public and political opinion towards NFM, with individuals and communities considering the implementation/support of schemes (Kinver, 2015; Corbridge Flood Action Group, 2016; McAlinden, 2016; Pang Valley Flood Forum, 2016; Wiggins, 2016).

1.2   Justification for research

It is important that the potential effectiveness of NFM be appraised for its ability to support the delivery of flood risk management (FRM) schemes in rural catchments. Lane (2008), Dadson et al. (2017) and the Environment Agency (2017) identified a lack of quantifiable evidence, both of monitoring post-installation as well as hydrological modelling. In cases in which NFM interventions have been simulated, modelling commonly targets the riparian area with a 1D or 2D-1D model, which poorly represent spatially distributed interventions.

Of the NFM case studies that inspire a high degree of confidence, many are heavily gauged, have significant data availability or have formed part of a demonstration catchment where funding regulations for a FAS are not commonly enforced. This means for a typical ungauged, data-sparse catchment there is minimal guidance and transferable case studies on how to appraise and implement an NFM scheme. This research seeks to contribute to filling that knowledge gap by

developing advice/a case study for a flood alleviation scheme using NFM, SuDS or diffuse pollution techniques for a previously ungauged catchment using minimal data.

The study catchment for this research is Tutta Beck in County Durham, where three properties are at immediate flood risk from a canalised and constrained watercourse. A FAS for this catchment was challenging due to limitations on benefits available and heritage designations near the receptor, which preclude a traditional protection strategy. Therefore, a low-cost NFM approach is desired to deliver the flood mitigation benefits within the budget of the scheme. The previously ungauged nature of the catchment provides an opportunity for hydrological modelling to be tested in a catchment with minimal available data. This is typical of the challenges a Risk Management Authority (RMA) would be faced with when developing a scheme.

1.3 Research aim and objectives

With regard to this research, it was fundamental for research outputs to integrate with the FAS being led by the local authority. To this end, a common theme throughout the research was the appraisal of feasible techniques that could be used in a functioning agricultural catchment, with a preference towards sustainable and minimal maintenance interventions. The primary aim of this thesis was **to investigate, using hydrological modelling tools, the potential for reducing flood risk using Natural Flood-Risk Management (NFM), Sustainable Drainage Systems (SuDS) and land management techniques and interventions.** This was achieved through the following objectives.

1. The development of a framework for Risk Management Authorities for investigating feasibility of delivering a Flood Alleviation Scheme using Natural Flood-Risk Management

Case studies using NFM often rely on knowledge, experience and complex modelling that are not available to most Risk Management Authorities. Furthermore, many schemes are unable to compensate landowners sufficiently to accept inundation of land. This research aims to provide a mechanism to support the delivery of such schemes, minimising the time and cost required to work on them and securing their delivery.

2. To support the development of a Flood Alleviation Scheme for the Tutta Beck catchment that minimises impact on agriculture

Agricultural function is an essential part of the Tutta Beck catchment and it is important to maintain this function throughout the FAS, avoiding the purchase of land and minimising costs. Retaining agricultural function while delivering flood mitigation benefits supports the transfer of learning from this to other agricultural catchments and minimises impact on the rural economy.

3. To determine the potential impact rural land management interventions could have on flood risk and if this hazard reduction is sufficient to protect receptor properties

Although significant FRM investment will be required long into the future, recent events and projected climate change suggest catchment management needs to change to reduce the hydrophobic nature of catchments. This objective identified whether or not reduction in flood risk for the Tutta Beck catchment could be delivered through changes in agriculture or whether or not FRM/NFM-specific techniques are required. This objective was addressed through hydrological simulations using the CRUM3 model. The approaches considered were vegetation change within the catchment, increased attenuation of flood flows, debris dams within the channels and combinations of these different measures. The evidence from this approach could support the integration of agricultural management with FRM and vice versa.

4. To assess whether or not SCIMAP-Flood, as compared with other approaches, is a suitable mechanism for targeting Flood Risk Management interventions

FRM authorities could target simulations using singular catchment characteristics such as steep slopes, runoff, susceptible land covers or highly drained areas. This objective seeks to appraise whether or not SCIMAP-Flood risk mapping is more effective at targeting interventions than these other techniques and, thereby, to justify its use in other catchments.

1.4   Thesis structure

This chapter has introduced the research aims and briefly introduces the challenges to NFM delivery both in the Tutta Beck catchment and elsewhere. Chapter 2 appraises the relevant literature, thereby, identifying challenges, the techniques available and case studies of such interventions. Chapter 3 introduces the Tutta Beck catchment and the nature of flood risk. Chapter 4 outlines the methods employed to address the research aims/questions. Chapters 5, 6, 7 and 8 present the results from hydrological modelling. Chapter 9 presents the discussion of results and the project conclusion.

Chapter 2   Literature Review

2.1 Introduction

This chapter reviews FRM literature, specifically, NFM, SuDS and diffuse pollution techniques. Section 2.2 introduces the catchment management approach, Section 2.3 outlines the responsibilities for flood management and Section 2.4 introduces the cost-benefit approach. Section 2.5 reviews the impact of agriculture on rural catchments and Section 2.6 reviews mitigation measures and their spatial distribution. Section 2.7 introduces hydrological modelling and the potential for informing flood management decisions. Section 2.8 summarises the chapter.

2.2 Catchment-scale FRM

Catchment management aims to restore a landscape's ability to manage the source of flood waters.
(SEPA, 2015)

The government's flood and coastal erosion risk management strategy promotes the use of NFM and SuDS (Nisbet & Thomas, 2008; Pitt, 2008; Defra & Environment Agency, 2011, 2014). NFM can be grouped into three delivery areas: upper, middle and lower catchment (Figure 2.1). The Flood Risk Management (Scotland) Act (2011) uses the concepts in Figure 2.1. SEPA (2015) produced guidance with regard to NFM, citing benefits to longevity and an increased standard of protection for existing defences as well as mitigation of the impact of predicted climate change on the number and severity of flood events. NFM, catchment management and SuDS all aim to influence the flood hydrograph in a similar way to Figure 2.2, lowering and elongating peak flows (Wilkinson, 2013). NFM does have challenges. Figure 2.1 shows agricultural land is commonly the main target for inundation through NFM (Hill, 2011) and this can have a negative impact on the rural economy. Reconnecting the floodplain for storage can require land purchase or other compensation payments. Examples of the latter include: payment per flood, payment for ecosystem services (Rose, 2014) or agri-environment agreements such as the Countryside Stewardship scheme and catchment-sensitive farming (CSF).
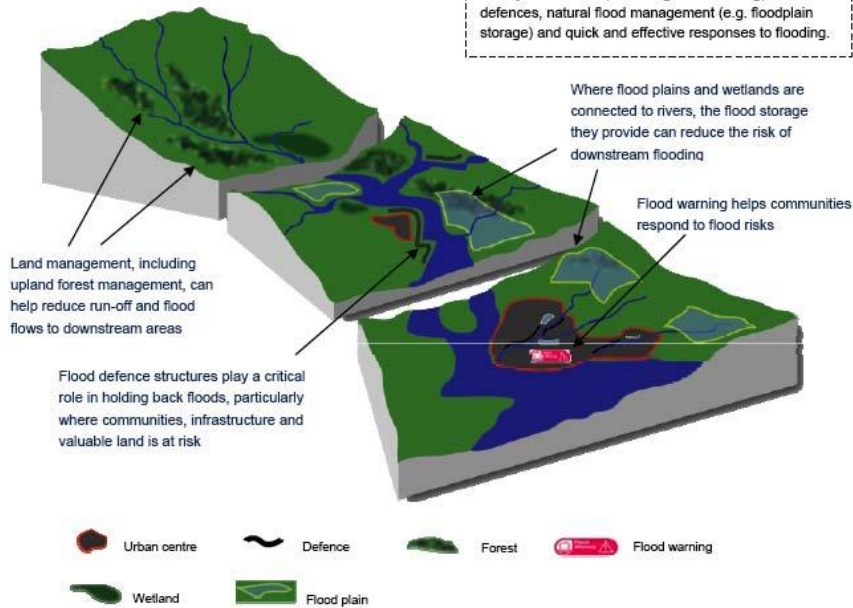
Figure 2.1 **Interactions across the catchment and areas to target (Flood Risk Management (Scotland) Act, 2011).**
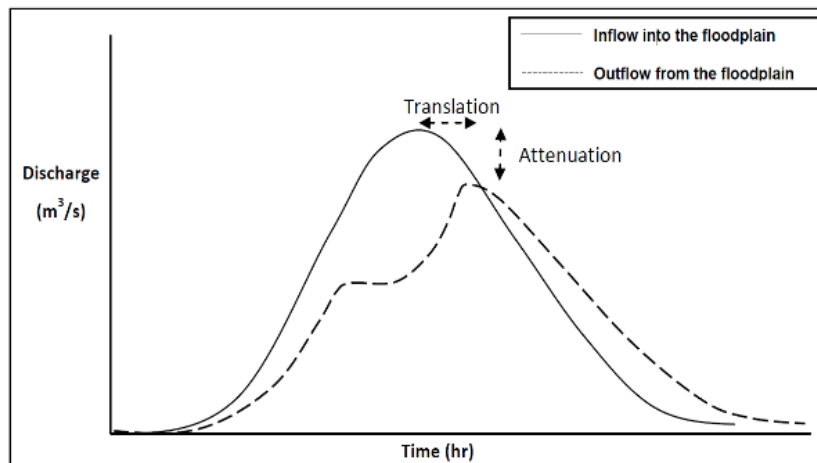
Figure 2.2 **Flood hydrograph showing the delay and decrease in peak proposed through NFM and floodplain connectivity (Morris et al., 2004; Hill, 2011).**

2.3 Responsibility for managing flood risk

The Department for Environment, Food and Rural Affairs (Defra) has the overriding responsibility for policy and advising ministers (Defra & Environment Agency, 2013) and its latest policy is derived from the Flood and Water Management Act (2010) and the EU Water Framework Directive [WFD] (European Union, 2000; Defra, 2014). The Department for Communities and Local Government and

the Cabinet Office also influence flood and coastal erosion risk management (FCERM) (Defra & Environment Agency, 2011).

The EA reviews FCERM strategy, implements policy and manages flood risk on main rivers and tidal areas (Defra & Environment Agency, 2011), as well as developing a six-year plan of works and allocating project funding.

The lead local flood authority (LLFA), typically the district or county council, is responsible for flood risk from ordinary watercourses and surface water. Its role is to develop capital projects and request funding as flood defence grant in aid or a local levy alongside Planning and Land Drainage Act (1991) responsibilities.

Landowners have riparian rights and responsibilities (Environment Agency, 2014) enforced through the Land Drainage Act (1991), which requires them to receive and discharge water in its natural quality and quantity.

2.4   Cost-benefit analysis

Cost-benefit analysis assigns a monetary value to benefits and drawbacks, enabling efficient evaluation of the FRM schemes (Layard & Glaister, 1994). In England, cost-benefit analysis is based on six outcome measures from a scheme, the main driver being Outcome Measure 2s, which focuses on moving houses between specific risk categories (Office of National Statistics, 2015). To receive any funding, a scheme needs to deliver, at the minimum, parity between identified costs and benefits with different funding sources restricted to specific ratios. Competition and strict financial justification increase pressure on schemes, which means that their instigating authorities are investigating innovative solutions, including partnership working and new techniques such as NFM and SuDS, to improve cost-benefit ratios. Defra accepts that implementing NFM has challenges, including demonstrating the benefits of remote interventions and securing contributions from partnership working (Craig, 2016), and has developed a new NFM research and development programme.

The cost-benefit approach has limitations, most notably in valuing the natural environment or an individual's property, and personal interpretation has significant variance here (Layard & Glaister, 1994). On the Holnicote Estate in Somerset, the approach used was payment for ecosystem services to reimburse farmers for changes to farm management, allowing temporary inundation of fields. The approach was successful because the value of the land increased due to the ecological improvements which in turn improved tourism appeal (Rose et al., 2010; Rose, 2014; National Trust, 2015; Rogers et al., 2015; Rose et al., 2015). Further limitations include: projected value of assets (Hanley & Spash, 1993); projected effectiveness given climate change (SEPA, 2015); and impacts elsewhere (Calder & Aylward, 2009).

2.5   Impact of agriculture on rural catchments

Agricultural catchments can generate a hydrophobic response to rainfall with high runoff, extensive drainage networks and straightened watercourses. High hydrological connectivity is synonymous with flood risk generation in rural catchments and the controls can be defined as those influencing infiltration (Horton, 1941; Jenny, 1946) or those influencing the transmission of overland flow (Bracken & Croke, 2007; Reaney et al., 2011b; Reaney et al., 2014). Agriculture controls multiple characteristics across many catchments, including vegetation (Ludwig et al., 2005), organic matter (OM) and soil structure (Boorman et al., 1995). It also significantly influences hydrology and flood risk generation.

2.5.1   Compaction

Compaction is common across farmland because machinery and animals compress soils. This damages structure, reduces pore spaces and changes rainfall response (Hamza & Anderson, 2005; Kurz et al., 2006; O'Connell et al., 2007: Posthumus et al., 2008; Smith, 2012; Pearson et al., 2015; Pearson, 2016). Compaction has many forms: surface crusting through vehicles or livestock (Moore & Singer, 1989); poaching through livestock trampling, for example, near troughs and feeders

(Mulholland & Fullen, 1991); cultivation pans through ploughing and crop rooting (Greenland & Pereira, 1977; Akker et al., 2003); and deep compaction through heavy vehicles (Soane et al., 1981).

Carrol et al. (2004) found compacted fields can have infiltration rates 60 times lower than in woodland areas. Under wet conditions, soils are unable to resist loading from heavy machinery (Kondo & Dias Junior, 1999) increasing likelihood of compaction (Holman et al., 2003). There is a positive correlation between compaction and: number of passes (Bakker & Davis, 1995); increased tyre pressure (Boguzas & Hahansson, 2001); and axle load. All of these influence compaction depth (Soane et al., 1981). Improved knowledge of the relationship between soil moisture and shear strength helps plan tillage and farm movement (Hamza & Anderson, 2005), and enables suitable tyre pressures to be set (Boguzas & Hahansson, 2001).

2.5.2   Vegetation

Vegetation influences hydrology and soils, generating macropores and disturbing overland flow (Greenway, 1987; Wilcox & Breshears 1995; Tongway & Ludwig, 1997; Angers & Caron, 1998; Bronstert et al., 2002; Wilcox et al., 2003; Ludwig et al., 2005; Reubens et al., 2007; Confor, 2015; SEPA, 2015). Vegetation also has an impact on soils and hydrology through its root network, which can stabilise soils and mitigate compaction (Oades, 1993; Reubens et al., 2007). Ludwig et al. (2005) theorised that vegetation generates a positive feedback loop (Figure 2.3). The current catchment vegetation is managed for agricultural productivity (Parry et al., 1992), and this has a negative impact on natural processes (Lunt et al., 2010, Moors for the Future Partnership, 2015).
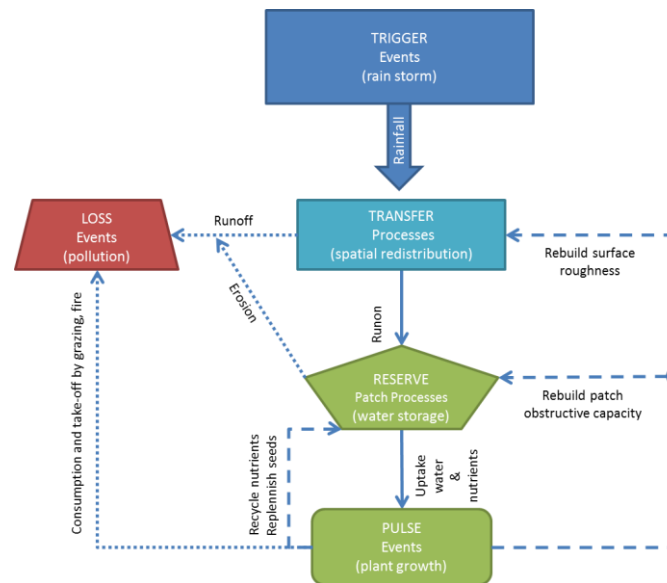
Figure 2.3 **Flow diagram showing trigger–transfer–reserve–pulse (TTRP) framework. Direct flows are solid lines, feedbacks are dashed lines and flows out of the system are dotted lines (Ludwig et al., 2005).**

2.5.3   Drainage

Drainage can take many forms. It is used to remove water to maximise productivity and the 1957 farm improvement grant supported the extensive installation of land drainage (Robinson, 1986; NFU, 2008). Land drainage includes straight channels that can disconnect floodplains. This increases conveyance (Acreman et al*.,* 2003; Bullock & Acreman, 2003; Transport Scotland, 2009), which can increase flood risk downstream (Bronstert 1995; Bronstert et al., 1999; Kundzewicz & Takeuchi 1999; Longfield and Macklin 1999; Kundzewicz & Kaczmarek, 2000; Bullock & Acreman, 2003).

2.5.4   Changes in agriculture

Since the Second World War, agriculture has changed significantly and is now carried out on an industrial scale. These changes have made catchments prone to runoff, soil erosion and diffuse pollution (O'Connell et al., 2007). Farm holdings in England and Wales have fallen from around 440,000 to 170,000 and workers from around 1 million to 180,000. Most of these changes occurred between 1950 and 2000 (Wilkins, 2000; Zayed, 2016). The result of larger farms with fewer workers has been an intensification of land use and greater mechanisation that can increase compaction.

The 1957 Agriculture Act provided price guarantees for items. This drove unsustainable production

(Bowler, 1979; Bowler & Ilbery, 1987; Wilkins, 2000; NFU, 2008; Zayed, 2016), which culminated in

'food mountains' in the 1970s and 1980s (European Commission, 2012; European Commission,

2016). The Common Agricultural Policy (CAP) has since shifted from artificial market support towards

a market-driven agricultural system, introducing sustainable directives alongside environmental,

ecological and water quality improvements. Figure 2.4 shows the key changes in agriculture

throughout the twentieth century. Most of the UK consists of agricultural land (Parry et al., 1992),

this being about 76% of the land area. Grasslands represent 65%, with 31% being rough grazing

(Humphreys et al., 2005).

Chart 1: Total arable area on British/UK farms
million hectares

Chart 5: Numbers of cattle on British/UK farms
millions

Chart 6: Number of sheep on British/UK farms
millions

Chart 10: Index of total factor productivity of UK agriculture
1973=100

Great Britain

UK, Total arable land

UK

Great Britain

UK

Great Britain

Current series

Historical series

1920

Supply–demand relationship is decoupled due to price support

Increases in production
Increases in productivity
Increases in cattle numbers
Fluctuation in sheep numbers
Rapid reduction in number of farm workers
Slow reduction in arable area

Farm production greatly exceeds demand and surplus is stored leading to food mountains

Shift towards sustainable agriculture away from overproduction

1920: Agriculture Act

1930: Land Drainage Act

1937: Agriculture Act

1947: Agriculture Act
Food independence the driving factor
Price support – intensification and increased production

1954: Meat rationing ends

1973: UK Joins Common Market and CAP

1974: Control of Pollution Act

1984: Milk quotas
Rapid reduction in dairy herd

1988: Set-Aside Regulations
BSE Order

1991: Nitrates Directive

1992: MacSharry reforms
Shift from product support (price support) towards producer support (income support)

1995: Environment Act

2000: Water Framework Directive

2001: Foot and mouth disease

2003: Reform of CAP

2007: UK Climate Change Bill

2008: CAP Health Check

2016: UK leaving the EU

Figure 2.4 **Graphs showing British/UK agriculture from 1920 (Bowler, 1979; Bowler & Ilbery, 1987; Wilkins, 2000; O'Connell et al., 2007; NFU, 2008; European Commission, 2016; Zayed, 2016).**

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2.6   Mitigation measures

Flood mitigation/alleviation is not designed to prevent floods but is concerned with measures to reduce the overall impact of flooding. Mitigation can include increasing resilience and increasing evacuation time as well as reducing the speed/depth of flood waters and is dependent on the type of flood risk. The form and type of mitigation measures are strongly linked to their spatial targeting. Figure 2.5 conceptualises the management train approach of SuDS, which is equally applicable to NFM. Table 2.1 identifies the interconnectedness of NFM and SuDS techniques and pinpoints approaches supporting the transfer of learning from both disciplines.

1 Prevention
Good housekeeping and site design to reduce and manage runoff and pollution, eg land-use planning, reduction of paved surfaces

2 Source control
Runoff managed as close to the source as possible, eg using green roofs, rainwater harvesting, permeable paving, filter strips

3 Site control
Runoff managed in a network across a site or local area, eg using swales, detention basins, public realm SuDS components for attenuation and treatment. Also, flow should be slowed using overland conveyed routes

4 Regional control
Downstream management of runoff for a whole site/catchment, eg retention ponds, wetlands

Figure 2.5 **SuDS treatment train (Lead Local Flood Authorities of the South East of England, 2013).**

Table 2.1 **The SuDS and catchment management/NFM interrelationship**

	Source	Pathway/conveyance	Receptor/end of pipe	System consequence
Traditional urban drainage	Impermeable hard surface with drainage • High runoff rate • Low retention ability • Rapid removal of water • Blocked gullies can lead to localised pluvial flooding	Pipes, culverts and canalised watercourses • High conveyance rate • Low retention/storage ability • Removes water from area efficiently • Can suffer from blockage • Finite capacity	Discharge to watercourse or surcharging of sewer (Isaaman, 2014) • Discharge can be restricted/blocked • High erosivity of discharging water • Capacity restriction due to design standards in Sewers for Adoption (2013)	• Designed to convey water to outlet rapidly • Can overwhelm watercourse • No water quality improvements • Maintenance challenges
SuDS option	Permeable paving (BGS, 2016) • Replicates natural infiltration • High degree of roughness slows flow • Storage in void spaces • Provides a treatment stage	Swale with check dams (Atelier Groenblauw, 2016) • High degree of roughness slows flow • Check dams encourage attenuation • Larger capacity than most pipes	Attenuation pond/basin (Collins, 2015) • Stores water before discharge • Safe designated storage area • Water quality improvements	• Slow flow of water through the system • Multiple diffuse storage locations • Multiple treatment stages for water quality improvements • Cheaper solution • Maintenance often cheaper
Current agricultural catchment	Compacted smooth surface • High runoff rate • Low water retention ability • Rapid removal of water • Blocked land drainage/ditches can cause localised flooding	Straight ditching/drainage • High conveyance rate • Low retention/storage ability • Removes water from area efficiently • Can increase erosivity of flows	Flood barrier/wall • Receptor protection has finite height • Often sole intervention	• Rapidly responding hydrograph • Once failed, flooding almost certainly has an impact on the receptor • No water quality improvements • Maintenance challenges
CaBA	Soil/land improvement • Improves infiltration (Cumbria Farm Environment Partnership, 2013) • High degree of roughness slows flow • Storage in void spaces • Removes compaction	Remeandering (Tweed Forum, 2015) • High degree of roughness slows flow • Encourages floodplain attenuation • Increased water retention	Flood storage areas • Stores water before receptor • Safe designated storage area • Water quality improvements • Storage can be overwhelmed – distance provides buffer to receptor • Easily monitored to provide flood warnings	• Slow flow of water through the system • Multiple diffuse storage locations • Water quality improvements • Can be cheaper solution • Maintenance easier • Reduces and delays flood peak

2.6.1 Source management

The source of flooding is not the receptor but can be described as the conditions throughout the catchment that generate the high flows. Source management targets the issues of impeded infiltration, runoff and connectivity. Reaney et al. (2014) conceptualised source management by thinking about a landscape on a point scale, stating that at each point there is either a transfer of water or not. This idea built on concepts of hydrological connectivity across the landscape (Reaney et al., 2011a; 2011b; Reaney et al., 2014). Mitigation in the source areas seeks to influence these transfers by reducing this connectivity (Reaney et al., 2011a; 2011b; Reaney, 2014).

2.6.1.1 Spatially targeted vegetation planting

Vegetation reduces overland flow and erosivity through canopy interception, infiltration improvements and disturbing overland flow (Sanchez, 1995; Vought et al, 1995; Descroix et al., 2001; Bronstert et al., 2002; Chaplot & Bissonais, 2003; Bronick & Lal, 2005; Ludwig et al., 2005; Burton et al., 2007; SEPA, 2015). The Moors for the Future research project found vegetation reduced and delayed peak flows (Allot et al., 2015; Nisbet et al., 2015) with similar findings reported by the Forest Research Group (Thomas & Nisbet, 2007; Nisbet et al., 2015). Spatially targeted woodland can deliver flood risk benefits (Vought et al., 1995; Nisbet & Broadmeadow, 2003; Nisbet, 2004; Thomas & Nisbet, 2007; Nisbet & Thomas, 2008; Nisbet et al., 2015). As an example, in Glen Clova, woodland has been targeted above the 400m contour to provide water quality and quantity improvements (River South Esk Catchment Partnership, 2015). Newson (2017) suggested shallow root systems in commercial forestry may not be suitable for FRM function.

Agroforestry integrates trees across farmland (Hamer, 2012), improving water quality and diversifying farm income (Seobi et al., 2004). Vegetation treatments can reduce runoff in a range 1–10% (Udawatta et al., 2001), but the scale, type and spatial targeting of vegetation limit this approach. Pontbren demonstrates that the integration of woodland with farmland can be beneficial to the farm business. The project aimed to reduce dependency on industrial farming and subsidies

(Keenleyside, 2013), and this included reducing livestock densities (Wales Rural Observatory, 2013).

Shelter belts can reduce runoff (Keenleyside, 2013), and Marshall et al. (2006) observed that tree

planting with sheep exclusion significantly reduced runoff. Carroll et al. (2004) found infiltration

rates in tree-planted areas were up to 60 times higher than those in adjacent grazing fields and that

measurable improvements were observed only two years after planting (Marshall et al., 2006).

2.6.1.2   Cover cropping and green manure

Cover cropping is used to protect soils rather than leaving them bare or covered with stubble,

reducing susceptibility to erosion (Browning et al., 1996; Dabney et al., 2007). Cover crops can

improve infiltration, slow runoff and reduce soil erosion (Dabney, 1998), and they are supported by

CSF with agri-environment funding (Northumberland CSF Steering Group, 2016a; Natural England,

2017). The cover crop chosen influences the benefits (Kaspar et al., 2001), for example, deep-rooting

radishes provide benefits for compaction alongside green manure and OM provision.

Response to OM treatment varies: grasses can improve water-stable aggregates and soil structure;

peat and slurry treatment can increase water retention (Ekwue, 1990; Zhang, 1994); and green

manure can improve and stabilise soil structure, increasing resistance to degradation (Thomas et al.,

1996). Hamza and Anderson (2005) identified several ways in which OM influences soil

compactibility, including: binding soil mineral particles (Tisdall & Oades, 1982; Zhang, 1994);

reducing aggregate wettability (Zhang, 1994); and increasing mechanical strength of aggregates

(Quirk & Panabokke, 1962). Halvin et al. (1989) found more organic carbon and nitrogen content was

retained with greater stubble remains. Quirk and Panabokke (1962) stated that cultivated

aggregates wetted more rapidly and Zhang (1994) found humification increased porosity and

reduced tensile strength.

2.6.1.3   Farming practices

Traditional farm management and support for the CAP/subsidies led to unsustainable exploitation of

catchments. In England Natural England is leading a change in farming practises to improve natural

capital, water quality and reduce environmental degradation (Natural England 2012; 2015. Pontbren demonstrates that industrial farming does not necessarily increase profits but ties farmers into a cycle of increasing inputs (Keenleyside, 2013). Conversely, low-input techniques have been shown not to have a negative impact on profits (Keenleyside, 2013). Dunn (2014) stated that improved farming practices benefited their farm in Cumbria. The land stewardship approach (European Union, 2000) involves responsible land use to minimise the impact agriculture can have on land.

A key change is cross-slope cultivation; this can be cost neutral while increasing surface roughness, retaining soil moisture and reducing soil erosion (Defra, 2007; PINPOINT, 2017) and can be enhanced using vegetation buffers. Mitigating soil erosion and rill formation can generate savings in the region of £690 per 10ha of a winter wheat crop (PINPOINT, 2017). Many farmers are hesitant to adopt this, primarily for efficiency, as field systems were designed with movements up and down slope. Second, there is a risk of machinery overturning on steep slopes; and third, water retention could have an impact on yield.

The risk of toppling is individual to each machine and relates to the centre of gravity and width of the wheelbase. Toppling occurs when the centre of mass moves outside of the pivot point (ground contact of downslope wheel) and varies with height, width and weight, making it impossible to determine a single gradient (Health and Safety Executive, 2013). In situations in which downslope cultivation is necessary, mitigation can be used. This includes tramline disruptors (Deasy et al., 2008) and changing the timing of traffic.

2.6.1.4 Compaction removal and soil aeration

Soil aeration is an agricultural treatment promoting macropores and the intake of oxygen and nutrients into the soil for respiration (Grable, 1966; Smith, 2012). Soil aeration improves natural function, bioturbation, water-holding capacity and root growth (Unger & Kaspar, 1993), and poor aeration can limit seedling development, which has an impact on yield (Huang & Scott NeSmith, 1999). Soil aeration techniques include: a spiked roller disrupting shallow compaction (<20cm) (Farm

Northwest, 2011; Smith, 2012); sward lifter subsoilers (variable depths), which work on the principle of a blade with 'wings' running laterally through the soil and splitting compacted layers (Droy, 2010); and a shaker aerator (>20cm). These techniques enhance infiltration and can mitigate saturation-driven overland flow (Smith, 2012; RDPE Northwest Livestock Programme, 2012; Eden Rivers Trust & ALFA, n.d.; Eden Rivers Trust and saving Eden, 2015; ALFA, 2016).

2.6.2 Flow interception and runoff attenuation features

This section targets the interception and attenuation of runoff, which delays the discharge of water off the hillslope into the watercourse. These features focus on hydrological connectivity discussed in Reaney et al. (2011a; 2011b; 2014) and Bracken and Croke (2007). Catchment topography and vegetation dictate connectivity (Reaney et al., 2011a; 2011b; 2014) and interventions should consider these processes (Wilkinson & Quinn, 2010). In Belford in Northumberland, field-scale interventions using runoff attenuation features (RAFs) were developed (Quinn et al., 2007; Wilkinson et al., 2008; Wilkinson & Quinn, 2010; Barber & Quinn, 2012; Wilkinson, 2013; Quinn, 2015; Barber, 2016; Hetherington, 2016; Wilkinson, 2016), a concept also utilised at Towcett Farm in Cumbria, (Barber & Reaney, 2016).

2.6.2.1 SuDS

SuDs are predominantly used in urban developments; however, flood management authorities are retrofitting SuDS to manage existing flood issues (Villarreal et al., 2004; Gordon-Walker et al., 2007; Durham County Council, 2016; Northumberland County Council, 2016b; O'Donnell, 2016; Shaffer & Digman, 2016; Thorne, 2016;).

Spatially distributed SuDs can provide storage with minimal disruption and reduce the likelihood of a single feature being overwhelmed (Ballard et al., 2015; LASOO, 2015). The use of SuDS provides multiple benefits, including increasing time to peak, infiltration, and water quality improvements (Ballard et al., 2015; LASOO, 2015; O'Donnell, 2016; Thorne, 2016). The applications of SuDS can be

conceptualised as disturbing source-pathway-receptor relationships (Floodsite, 2016) similar to NFM.

2.6.2.2 Ditch of the future (DoF)

These structures combine conveyance and attenuation; they are wide and shallow and function like swales (Section 2.6.2.1). Barber and Reaney (2016) found these features provide similar benefits, including reduced sediment and agricultural pollutant load (Figure 2.6).
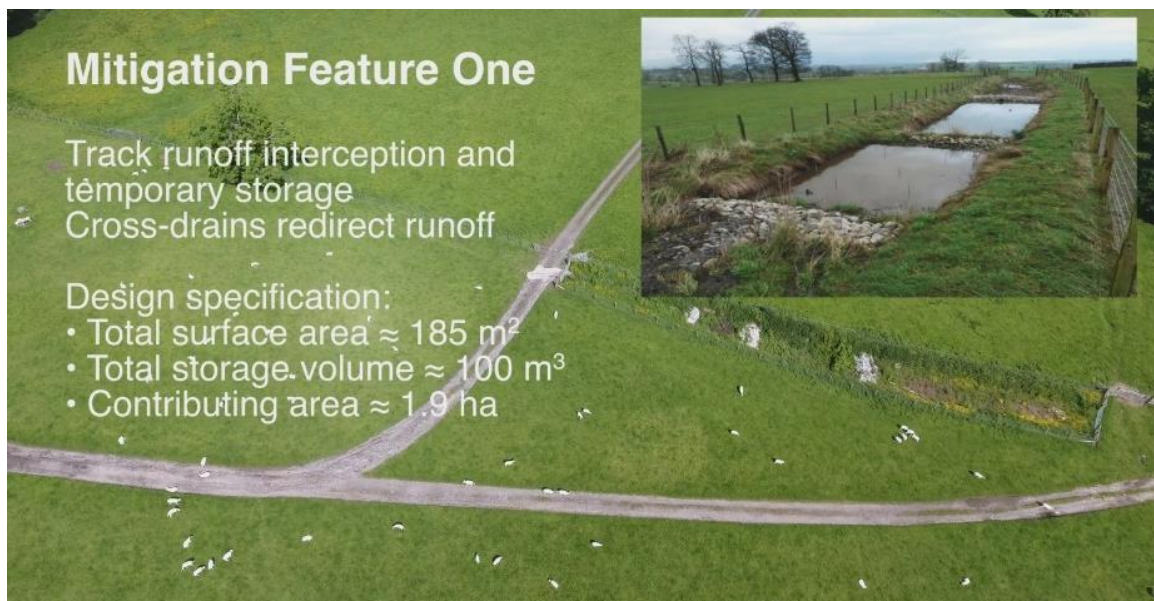
Figure 2.6 **Image of DoF feature with insert showing the attenuation of runoff from the track (Barber & Reaney, 2016).**

By incorporating a permeable base these features could incorporate infiltration and groundwater recharge. Using a similar approach to redesign drainage could increase catchment storage with minimal impact on agricultural availability.

2.6.2.3 RAFs

These features have been used in Belford in Northumberland to intercept, slow and store runoff (Quinn et al., 2007; Wilkinson et al., 2008; Wilkinson & Quinn, 2010; Barber & Quinn, 2012; Wilkinson, 2013; Hetherington et al., 2014; Nicholson et al., 2014; Quinn, 2015; Hetherington, 2016; Wilkinson, 2016; Fraser et al., 2017).
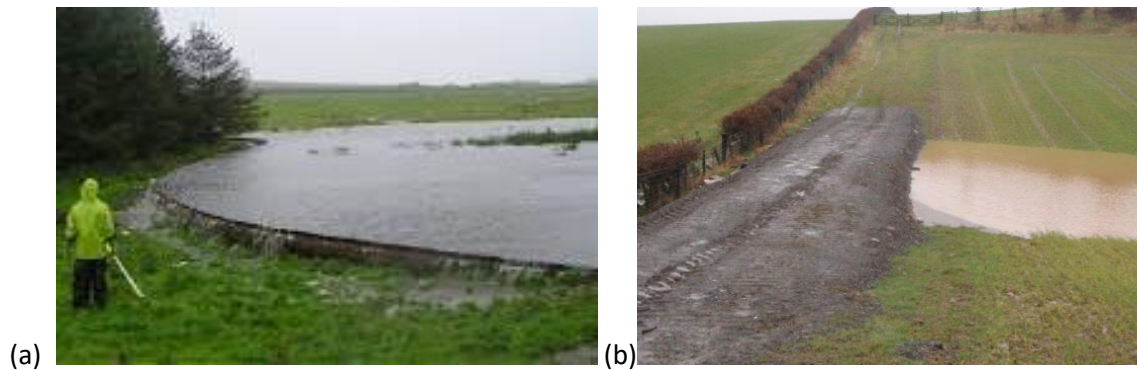
Figure 2.7 Images showing *(a)* wooden RAF at Belford; *(b)* trackway-bunded RAF (Wilkinson et al., 2010).

The use of RAFs was appraised in Wilkinson et al. (2008) but the results did not conclusively quantify their impact due to natural variation in inputs. However, since installation, the village has not flooded during events of similar magnitude to those that generated flooding previously (Wilkinson & Quinn, 2008; Wilkinson & Quinn, 2010; Wilkinson et al., 2010; Quinn, 2015). Spatial targeting was performed using GIS with LiDAR and digitised field boundaries (Nicholson et al., 2012), building on techniques used in Ripon (Posthumus et al., 2008). To demonstrate function, when installed, the pilot RAF (Figure 2.7(a) retained up to 800m^3, releasing that water slowly over a period of 8–12 hours (Wilkinson & Quinn, 2010).

Belford also used farm infrastructure as RAFs (Figure 2.7(b) (Wilkinson & Quinn, 2010), which reduced impact on the farmer, and a similar strategy was adopted in Alwinton in Northumberland (Fraser et al., 2017). These techniques compensate farmers for accepting temporary inundation by providing benefits and ensure long-term maintenance of features. These features can also provide multiple benefits (Barber & Quinn, 2012) because sediments could be redistributed on to fields, thereby reclaiming lost resource (Quinn, 2015).

Limitations of the GIS-targeting approach include the data requirements for this process, which are not always available. Strong landowner/farmer engagement was a key theme of the Belford and Alwinton projects, but this is not always possible. Furthermore, being able to access help with design and assessment without university support would not be feasible for a similar scale FAS.

2.6.3   Channel and floodplain

Mitigation can be targeted at the channel, making delivery simpler for local authorities with limited knowledge of 2D modelling capacity. Channel interventions can include: woodland (Section 2.6.3.1); large woody debris (sections 2.6.3.2 and 2.6.3.3); and reconnecting the floodplain (Section 2.6.3.4).

2.6.3.1   Riparian woodland

Riparian woodland serves two primary functions: intercepting runoff (Muscutt et al., 1993); and disturbing out-of-bank flooding (English Nature et al., 2002; Nisbet & Broadmeadow, 2003; Nisbet, 2004; Nisbet & Thomas, 2008). Riparian woodland has been used in: the Eden Demonstration Test Catchment (Eden DTC); the Adaptive Land for Flood Alleviation (ALFA) project (Smith, 2012; Barber & Reaney, 2016; Pearson, 2016; ALFA 2016); at Ripon (Posthumus et al., 2008); and at the Coalhouses Burn near Chatton in Northumberland (Renner, 2016). Buffer strips can increase infiltration (Greenway, 1987; Angers & Caron, 1998; Ludwig et al., 2005; Reubens et al., 2007), which improves soil structure (Oades, 1993) and reduces bank erosion. McLean et al. (2013) found woodland enhanced the ecological value of the river corridor (Hughes et al., 2001; Steiger et al., 2005). Woodland has been incorporated in CSF as an intervention technique (Figure 2.8) with financial support to insert woodland to mitigate flood risk. Most rivers would naturally be bordered by woodland (Gurnell et al., 2005); therefore, riparian afforestation can be said to reinstate the natural processes of slowing the flow and water retention (English Nature et al., 2002; Nisbet & Broadmeadow, 2003; Nisbet, 2004; Nisbet & Thomas, 2008). Thomas and Nisbet (2007) indicated that the primary benefit of riparian woodland for flooding would be to increase hydraulic roughness, and Kadlec (1990) noted leafy debris in woodland could enhance floodplain friction. Nisbet and Thomas (2008) claimed 40ha of planting could delay a 1% annual probability event by up to one hour.
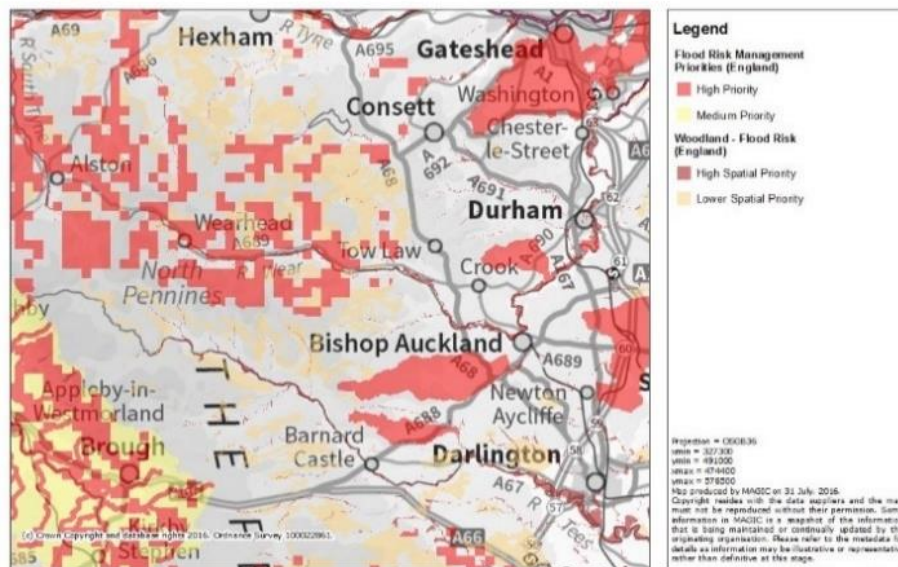
Figure 2.8 **Map showing woodland for flood risk (England) and FRM priority areas for CSF scoring system (MAGIC Map, 2016).**

2.6.3.2   Grip blocking

In small channels, grip blocking has been used to slow the flow and it also supports peatland restoration (Evans et al., 2005; Moors for the Future Partnership, 2015). On Kinder Scout, Odoni and Milledge (2015) identified the fact that grip construction influences its function and concluded that letter box slot gaps were most effective at retaining water but still enabling it to discharge. Slot gaps allow the head of water to produce a variable discharge rate, which reduces the chance of overtopping and the measure being ineffective (Odoni & Milledge, 2015). At Pickering Beck, wood and heather brash dams were used (Odoni & Milledge, 2015), which enabled suspended sediment to drop out (Moors for the Future Partnership, 2015).

2.6.3.3   Large woody debris (LWD)

This approach is common within NFM, restricting and slowing flow as well as promoting lateral spread on to the floodplain (Figure 2.9) (Quinn et al., 2007; Environment Agency, 2009b, 2009c; Odoni & Lane, 2010; Wilkinson & Quinn 2010; Wilkinson et al., 2010; Thomas & Nisbet, 2012; Quinn et al., 2013; Nisbet et al., 2015; Quinn, 2015; Fraser & Reaney, 2016a; Fraser & Reaney, 2016b; Lean, 2016; Fraser & Reaney, 2017; Fraser et al., 2017; Fraser & Reaney, 2018; Odoni et al., 2010). The

construction of features dictates their function. In Figure 2.9: (a) targets flow disturbance; (b and c) target discharge reduction and attenuation; and (d and e) target flow disturbance and reconnecting the floodplain. Use of LWD can promote flooding into water-tolerant woodland (Wilkinson et al., 2010; Spence & Sisson, 2015; Spence, 2016), which is fundamental to the rural SuDS project (Stroud, 2015; Uttley, 2017).

(a)   (b)   (c)

(d)   (e)
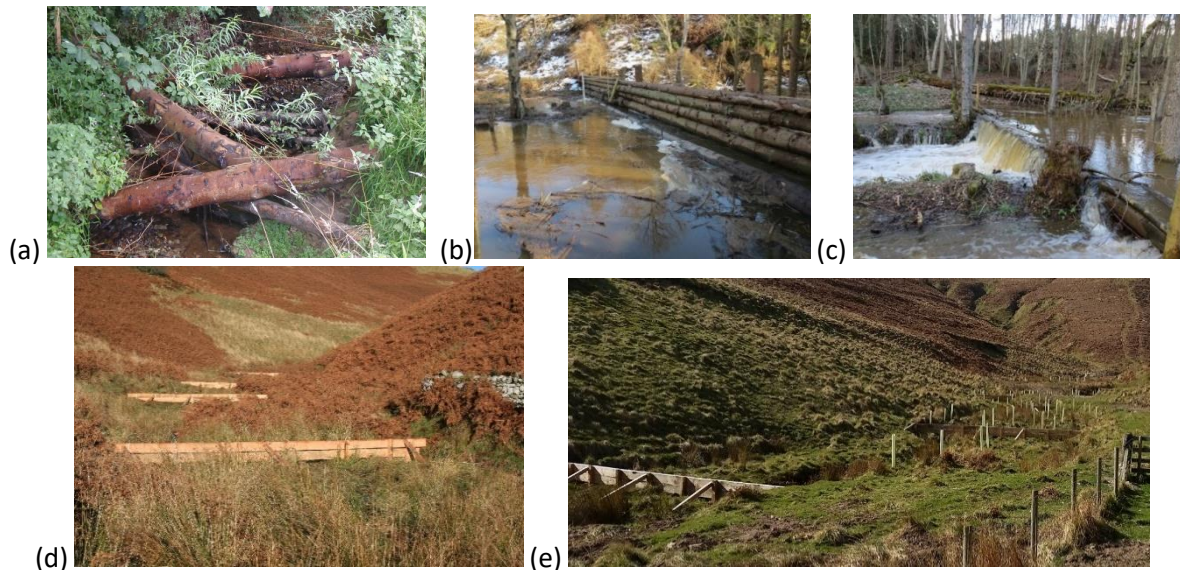
Figure 2.9 Images showing *(a)* flow disturbance at Hepscott in Northumberland (Royal Haskoning DHV, 2014); *(b and c)* timber bunds at Pickering Beck (Marrington, 2012); *(d)* timber barriers at Alwinton (Fraser et al., 2017); *(e)* timber barriers and willow planting at Alwinton (Fraser et al., 2017).

Linstead and Gurnell (1998) found naturally occurring debris dams typically form at a ratio of one barrier to 7–10 channel widths, which supported installations at Pickering Beck (Odoni & Lane, 2010; Odoni et al., 2010) and at Kinder Scout (Milledge, 2015; Milledge et al., 2015) and Alwinton (Fraser et al., 2017).

One issue with LWD is degradation, meaning inspection, maintenance and replacement costs could be expensive over the lifetime of the feature. This is difficult to address with current funding models because they prefer a single installation payment. A second issue discussed by Quinn (2015) is that NFM is opportune when phased and with features installed and monitored; learning is used to influence further phases. This method was used in Netherton in Northumberland, where sediment

traps constructed by Cheviot Futures (2012) were monitored. This helped inform the local authority FAS (Green, 2016a).

2.6.3.4 Reconnecting the floodplain and remeandering

There is movement on an international scale towards using floodplains to manage flood risk (McCartney & Naden, 1995; Morris et al., 2004; Svensson et al., 2006; Lane & Thorne, 2007; Lane 2008; Wilkinson et al., 2008; Wilkinson et al., 2010; Hill, 2011; Rose, 2014). Restoring natural floodplain processes reduces and elongates the hydrograph (Sholtes, 2009) and floodplain storage drains down after the flood peak has passed (Whiting & Pomeranets, 1997; Hill, 2011). Morris et al., (2004) suggest these areas should flood more readily and frequently to alleviate flood risk. Hill (2011) identified the fact that flat and wide floodplains maximise attenuation and friction, which provides greater benefits; as flow and depth increase the benefits of floodplain attenuation decrease (Archer, 1989).

Remeandering increases channel length and promotes the reestablishment of natural river processes and overflow of the channel. This work has been carried out on the Swindale Beck in Cumbria (Johnston, 2016; Restoring Europe's Rivers, 2016), on the River Lymington in Scotland (River Restoration Centre, 2013), on the Holnicote Estate in Somerset (Rose et al., 2011; Rose, 2014; Rose et al., 2015) and on Eddleston Water in Scotland (Tweed Forum, 2015). It is typically done to rehabilitate a straightened watercourse, as on Eddleston Water (Tweed Forum, 2015), or where incision creates high-flanking alluvial terraces (Rosgen, 1997). On the River Tall in Northern Ireland, online bays (Figure 2.10) created primarily for fluvial ecology could provide attenuation and dissipate the force of flood waters (Bankhead, 2013).
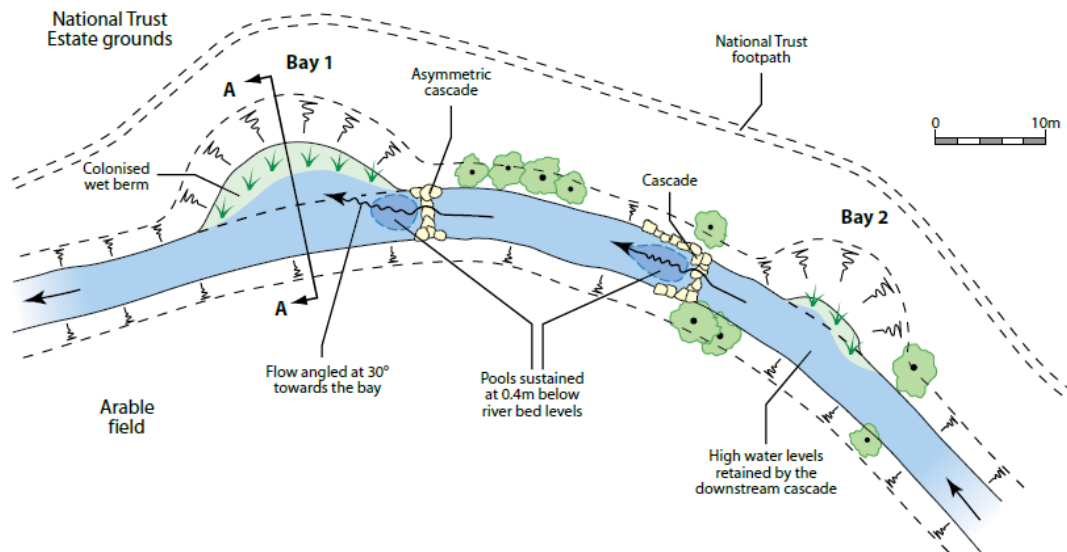
Figure 2.10 **Map showing bays and cascades on the River Tall in Northern Ireland (River Restoration Centre, 2013).**

Floodplain reconnection was a key measure in the scheme on the Holnicote Estate in Somerset, where a joint ecosystem services and FAS approach was adopted with meander extension and bank regrading (Rose et al., 2010; Rose, 2014). Rose (2014) suggested the scheme delivered reductions in peak flow and increased time to peak; however, estimation of response to interventions was needed to prevent flood peaks synchronising at the receptor and amplifying flood peak. The National Farmers Union (NFU) (NFU representative, 2015; Copeland, 2017) acknowledged channel management through farmland could be key in delivering flood risk reduction. Lorenz et al. (2009) suggest meander reinstatement could enhance ecosystem services, including wetland development. It is suggested that for flood control and water quality improvement 3–7% of temperate zone watersheds should be wetlands (Mitsch & Gosselink, 2000) and that for maximum effectiveness they should be targeted and spatially distributed.

2.6.4   Receptor protection

Traditional protection strategies are often required to complement NFM. In Alwinton, protection was installed to complement upstream interventions (Fraser et al., 2017). In Morpeth in Northumberland, upstream storage at the Mitford dam (renamed the Hargreaves dam in memory of

Jon Hargreaves) meant floodwalls in Morpeth were lower, access could be maintained and, most significantly, bridges in the town did not need raising.

2.6.4.1 Berms, levees and floodwalls

These structures have been used for hundreds of years and are still commonly used. However, their use needs to be fully appraised because, without consideration, the impact on flow could be ineffective or simply transfer flood peak downstream. This research will not simulate protection solutions; however, such measures may be required as part of a catchment management approach.

2.6.4.2 Property-level resistance/resilience

In many cases, flood risk cannot be totally removed. For example, in Corbridge in Northumberland, flood banks offer limited protection; therefore, many residents have installed measures to manage their flood risk (Northumberland County Council, 2016a). Resilience is defined as techniques that accept water into a property but limit the damage. Resistance is defined as techniques that prevent water entering a property; these can include, but are not limited to, flood doors, demountable barriers and sand bags (Harriman, 2016; Hiscock, 2016; Preston, 2016). Resistance can be thought of in terms of both active and passive measures: active measures require deployment, passive measures require no active intervention, an example being flood doors (Hendy, 2016). The fitting of such measures has, in recent years, been driven by government funding following a flood event. In 2013, the Repair and Renew Grant was used to fund flood mitigation for measures up to a value of £5,000 per property and was administered by local authorities on behalf of Defra (Fraser, 2015). Hendy (2016) identifies the fact that although these products can be high quality, their success requires high-quality installation as well.

2.7 Hydrological modelling

Funding regulations require evidence to demonstrate the benefits deliverable through a FAS; this is typically achieved through hydrological/hydraulic modelling. Models vary from simple closed data input and output models (Mulligan, 2004) and lumped catchment models (Beven, 2011) through to

complex, fully spatially distributed models and temporally variable models (Beven, 2001, 2011; Mulligan, 2004) that can consider diverse terrestrial and hydrological interactions (Beven & Germann, 1982; Beven, 1993; Beven & Freer, 2001; Beven, 2011; Beven & Brazier, 2011). The modelling process conceptualises and attributes parameters to complex processes in a much simpler fashion (Blöshl & Sivapalan, 1995). There are several factors that influence model selection and approach; these can include budget, required accuracy, output objectives, delivery timescales and data availability.

2.7.1 Model classification

Models vary in complexity and function depending on the requirements of the modelling. Metric or lumped catchment models use observations to characterise a system response to data (Wheater et al., 1993; Pechlivanidis et al., 2011), an example being the *Flood Estimation Handbook* (FEH) (NERC, 1999), which was derived from the UK *Flood Studies Report* (NERC, 1975). Metric models relate a regional analysis of model properties to physical and climatic catchment descriptors (Pechlivanidis et al., 2011). Such models are often used in cases in which catchment flow data is unavailable, or they can be used to extrapolate extreme events; uncertainty is often difficult to specify (Wheater, 2002; Pechlivanidis et al., 2011).

Conceptual models vary in complexity and structure (Pechlivanidis et al., 2011) and represent components perceived to be important at the catchment scale (Wheater, 2002). Some parameters in conceptual models cannot be physically interpreted directly or do not have measurability (Wheater et al., 1993). Some models cannot include all elements of hydrology, which compromises their applicability (Wagener et al., 2003; Beven, 2011). Wheater (2002) suggested there should be a balance between model complexity (to represent hydrology) and data (to support a complex representative model).

Physically based models represent hydrological processes using governing equations based on continuum mechanics (Pechlivanidis et al., 2011), which means that processes are measurable

(Beven, 2011). Modelling of physical properties at the catchment scale is predominantly driven by extrapolation from sampling; this transfer between scales causes uncertainty with regard to suitability due to high spatial and temporal variability in physical characteristics (Beven, 2004).

2.7.2   Different approaches to modelling

Different models have a different approach to generating results, each having benefits and drawbacks. The lumped catchment approach is commonly used to design interventions or appraise flood risk (CIWEM, 2009). This approach uses statistical techniques to convert rainfall to runoff and channel discharges (Wheater et al., 1993; CIWEM, 2009; Pechlivanidis et al., 2011). In cases in which observation data is obtainable, FEH data can be recalibrated to better represent the rainfall–discharge relationship of the catchment; this data is not commonly available. As such, data can be used from 'donor sites'; however, identifying suitable sites is not always possible (Dawson et al., 2006).

Steady state models are used for single event simulation, examples of these being Flood Modeller and XPSWMM. The XPSWMM model simulates an event (taken from the FEH) within a topographic representation of the catchment (Coombs, 2016; Innovyze, 2017), which enables the identification of risk areas. Additional modules within XPSWMM enable integration of infiltration and control structures (Coombs, 2016; Innovyze, 2017). SCIMAP (2016) is a steady state risk mapping model that appraises catchment connectivity using land cover data, topographic routing and proximity to watercourses (Reaney et al., 2011a; Milledge et al., 2012). Shore et al. (2013) state that with any connectivity assessment, both steady state and temporally dynamic, it is important to ensure an accurate representation of channels, ditches and drainage.

Fully distributed hydrological models use catchment characteristics to simulate response to rainfall. These require more inputs and accurate data to drive the model (Beven, 2001; Beven, 2004; Beven, 2011; Pechlivanidis et al., 2011, Shore et al., 2013), the benefits of this being the ability to simulate spatially distributed interventions over time; however, computational requirements are far greater

(Beven, 1993; Beven, 2001; Beven, 2004; Beven, 2011). A limitation of physically distributed models is the accuracy of connectivity. Shore et al. (2013) identified the fact that inaccurate channel and drain mapping could adjust transport times, connectivity and risk of saturation.

2.7.3   Modelling predictive uncertainty

Hydrological processes are complicated and, as such, hydrological models are becoming increasingly complex in order to represent these properly, resulting in many parameters to represent variation (Beven, 2011). The number of parameters and range of variables can generate a 'correct' result using 'incorrect' parameters, known as equifinality (Beven, 1993; Beven, 2001; Beven, 2006; Ebel & Loague, 2006; Vrugt et al., 2009; Beven, 2011). This concept was identified through Monte Carlo experiments that assessed discharges with different input parameter sets (Beven, 2001; Beven, 2006; Beven, 2011; Pechlivanidis et al., 2011). From this, the general likelihood uncertainty estimation (GLUE) approach was established, in which all possible parameter sets are appraised, following which a likelihood weighting is used according to the behavioural or non-behavioural relationship (Pechlivanidis et al., 2011). The weighting is the primary weakness of this approach because the behavioural relationship supported may not always be followed (Pechlivanidis et al., 2011).

2.7.4   Relevant hydrological models

Table 2.2 provides an overview of a selection of hydrological and hydraulic simulation models that can be applied in FRM studies. It is important that the selected model is fit for the purpose it has been commissioned for. In the case of NFM schemes it is important that models can consider the impact of spatially distributed interventions and those discussed in Section 2.6.

The lumped catchment model and SCIMAP-Flood Table 2.2 are primarily used for early appraisal of the catchment and identifying a suitable concept or long list of options. Use of additional models or other data is commonly required to design interventions and provide confidence in outputs.

In flood modelling, traditionally, 2D-1D linked models, such as HEC-RAS and InfoWorks ICM (Table 2.2) are used because these are well suited to simulating receptor protection and generating flood maps. However, they are not designed to simulate the techniques used by NFM and, as such, require discrete adjustments in their governing equations or modifications to roughness coefficients to simulate interventions. These simulations require significant technical knowledge to justify changes, particularly when requesting funding from a regulator. This also minimises transferability of any learning.

To this end, the more complex, fully spatially distributed, process-based hydrological models from Table 2.2 are suitable. Between model 'runs' the governing equations are not changed, meaning that the baseline hydrology remains the same and the changes are represented by adjustments to input data. This means that demand for technical expertise is reduced to setting up the model and starting off and processing model runs. The development of simulations can be undertaken by non-technical members of the team using GIS tools or similar without the need to change various elements in the model.

In most FAS, selection from the models available is commonly driven by acceptance of outputs by funders, cost of the model and available resources. With this research seeking to support knowledge transfer it is important that the correct model is chosen. Section 4.5 describes the process of selecting a suitable model through a review of Table 2.2 and other literature.

Table 2.2 **Examples of models available for simulating hydrology/flood risk mitigation**

Model	Model characteristics	Benefits	Limitations	Cost

Connectivity of runoff model 3D (CRUM3)	• Fully spatially distributed
	• Continuous temporal representation
	• Minimal data requirements
	  ○ Rainfall
	  ○ Digital elevation model (DEM)
	  ○ Topographic characteristics
	  ○ Soil and infiltration
	  ○ Land cover
	  ○ Channels
	• Discharge used for validation
	• GLUE approach
		• Outputs suitable for EA
		• High accuracy for high flows
		• Temporal representation allows multiple event analysis
		• Simulations created using readily available GIS software
		• Simulates spatial interventions
		• Can simulate spatial variation in land cover and infiltration
		• Numerous detailed outputs
			• Currently 50m resolution
			• Does not include drainage
			• Flow restrictions cannot be overwhelmed (vertical 'glass walling')
			• Detailed design required
			• Does not produce flood outline at the receptor
			• High computational requirements
			• Requires accurate data for catchment
				• Development model not commercially valued
				• High computational demand requires expensive high-performance cluster
				• GLUE approach essential and costly
				• Sourcing the data independently could be costly due to number of source licences required

SCIMAP-Flood Derived from SCIMAP (2016)	• Spatially variable
	• Steady state
	• Connectivity mapping
	• Minimal data requirements
	  ○ Topography
	  ○ Land cover
	  ○ Channels
	  ○ Gridded average rainfall (Tanguy et al. 2015)
		• Produces hydrological connectivity and flood sources risk map
		• Rapid to process
		• High resolution
		• Easy to adjust to replicate changes in management
		• Can simulate interventions
			• Single event/risk map
			• Cannot simulate hydrology
			• Does not simulate discharge
			• Uncertainty not produced
			• Requires accurate land cover, channel and topographic data
			• Does not integrate with positive or closed drainage networks
				• Free in UK using SCIMAP online
				• Sourcing the data independently could be costly due to number of source licences required

FEH updated to ReFEH	• Lumped statistical model • Generates catchment characteristics from sample catchments • Outputs transferable to most hydrological/hydraulic models	• Widely used in sector • Statistically based • Low data input requirements • Generates data at ungauged catchments • Minimal data requirements	• Limited catchment validation and assessment (Dawson et al., 2006) • Generic output • Requires detailed knowledge • Cannot simulate spatial interventions	• £295 base price • £1,000–£2,000 for additional modules to improve functionality • FEH web service could reduce costs to work on additional catchments
InfoWorks ICM, incorporating TUFLOW 2D engine	• 1D hydraulic model linked to a 2D terrain module • Can simulate incremental changes in the catchment (Simões et al., 2011)	• Hydraulic modelling of interventions • Outputs suitable for EA • Can simulate catchment scale • Rural and urban integration	• Detailed design for single event • Not temporally variable • Simulations driven by rainfall and river flow hydrograph • Requires accurate channel data	• £2,000–£3,000 (including training, support and updates) • Sourcing the data costly • Can produce flood hazard rating

	• Simulates both urban drainage and channel flows	• Simulates flood locations, depth and velocity	• No temporal variation in rainfall–runoff relationship	• Industry-approved outputs (Phillips et al., 2005; Evans et al., 2007)

HEC-RAS	• Minimal data requirements
	  o Topographic data LiDAR or similar
	  o Roughness values
	  o Channel cross-sections
	  o Discharge inputs
	• Commonly used to simulate infrastructure failure
	• Can be used to simulate increases in channel roughness, blockages and sediment accretion
		• Industry-approved outputs
		• Simulates flood locations, depth and velocity
		• 1D steady flow and 2D unsteady flow modelling
		• Sediment transport
		• Good for modelling on a watercourse
		• Industry standard software
		• Cross-sections required with risk of glass walling
		• Produces good-quality channel flooding data
		• Can simulate feature failure, blockages and roughness
			• Simulations driven by rainfall and river flow hydrograph
			• Requires accurate channel and drainage data
			• Not catchment scale model
			• Does not include rainfall–runoff representation
			• Multiple inflows can cause problems with accuracy
			• Need accurate cross-sections or channel data to model flood risk
			• Cannot simulate spatially diffuse catchment interventions
			• Issues with numeric instability during unsteady analysis
				• Free to download
				• Some add-on packages can be costly
				• Cost to train in its use can be expensive
				• Sourcing the data independently could be costly due to number of source licences required
				• Produces industry-approved flood extent, depth and velocity maps

SHE TRANS/MIKE SHE	• Deterministic, physically based, distributed model (Golmohammadi et al., 2014)
	• Continuous temporal representation
	• Minimal data requirements
	  o Rainfall
	  o Potential evapotranspiration
	  o Topography
	  o Channel network
	  o Channel cross-sections
	  o Water levels
	  o Groundwater depth
	  o Soil hydraulic characteristics
	  o Land cover
	  o Control structure dimensions
		• Catchment-scale simulation
		• Can simulate detailed flooding
		• Simulates all significant hydrological responses
		• Simulates catchment losses
		• Simulates spatial variable interventions
		• Represents rainfall–runoff relationship
		• Simulates significant hydrological processes
		• Simulates channel and structures using 1D hydraulic model
		• Animation of model run can be displayed
			• Simulations require detailed catchment knowledge to accurately represent hydrological processes
			• Simulations have high data requirements
			• Requires accurate channel and drainage data
			• Cannot simulate disconnected inflows (drainage)
			• Need accurate cross-sections or channel data to model flood risk
			• Limited access to source code
				• Full version $10,000
				• Simpler versions available
				• Add-ons are additional
				• Cost to train in its use can be expensive
				• Sourcing the data independently could be costly due to number of source licences required
				• Produces industry-approved flood extent, depth and velocity maps

2.8   Summary

This chapter has summarised the literature surrounding current issues concerning agricultural catchments and the interventions being considered to counteract the present hydrophobic response to rainfall. By introducing these options for NFM this section provides justification for simulation in FRM and the necessity for a distributed hydrological model to simulate spatial and temporal response to catchment interventions. Finally, case study literature demonstrating the various techniques that are being adopted and included in the NFM, land management and SuDS toolkits to mitigate flood risk was introduced.

Chapter 3   Catchment Description

3.1 Introduction

This chapter introduces the Tutta Beck catchment and research drivers. Section 3.2 describes the catchment characteristics and Section 3.3 describes human influences on the catchment. Section 3.4 introduces flood risk with regard to the catchment. Section 3.5 summarises the chapter.

3.2 Catchment characteristics

The Tutta Beck catchment (Figure 3.1) is a 7.06km^2, predominantly agricultural sub-catchment of the River Tees approximately 2.5km south-east of Barnard Castle in County Durham. Tutta Beck flows in an easterly direction from Kilmond Wood Quarry to Greta Bridge, discharging into the River Greta north of the A66 trunk road (Figure 3.1), which traces the northern boundary of the catchment.
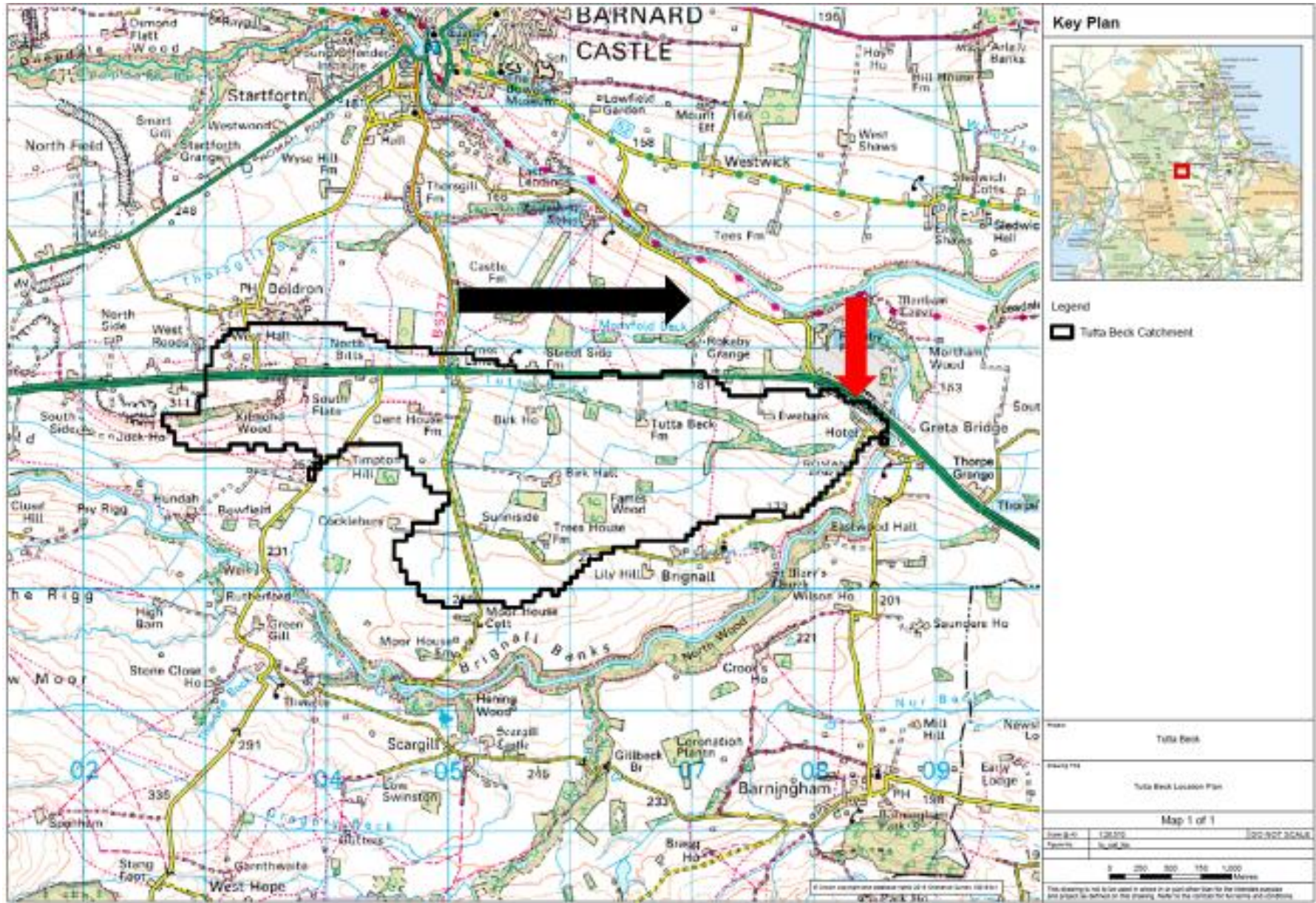
Figure 3.1 **The Tutta Beck catchment as shown on OS Landranger map 92 1:25,000. The black arrow denotes flow direction through the catchment and the red arrow denotes the location of the outflow and vulnerable properties as shown in Figure 3.15 and Figure *3.16*.**

3.2.1 Climate

The UK has a temperate climate with predominantly westerly weather patterns influenced by the Atlantic Ocean and the Gulf Stream, highlighted by higher rainfall to the west of the country (Figure 3.2). The study site lies to the east of the Pennines in Upper Teesdale, which has average annual rainfall levels of 900–1500mm (Met Office, 2016).

(a)   (b)
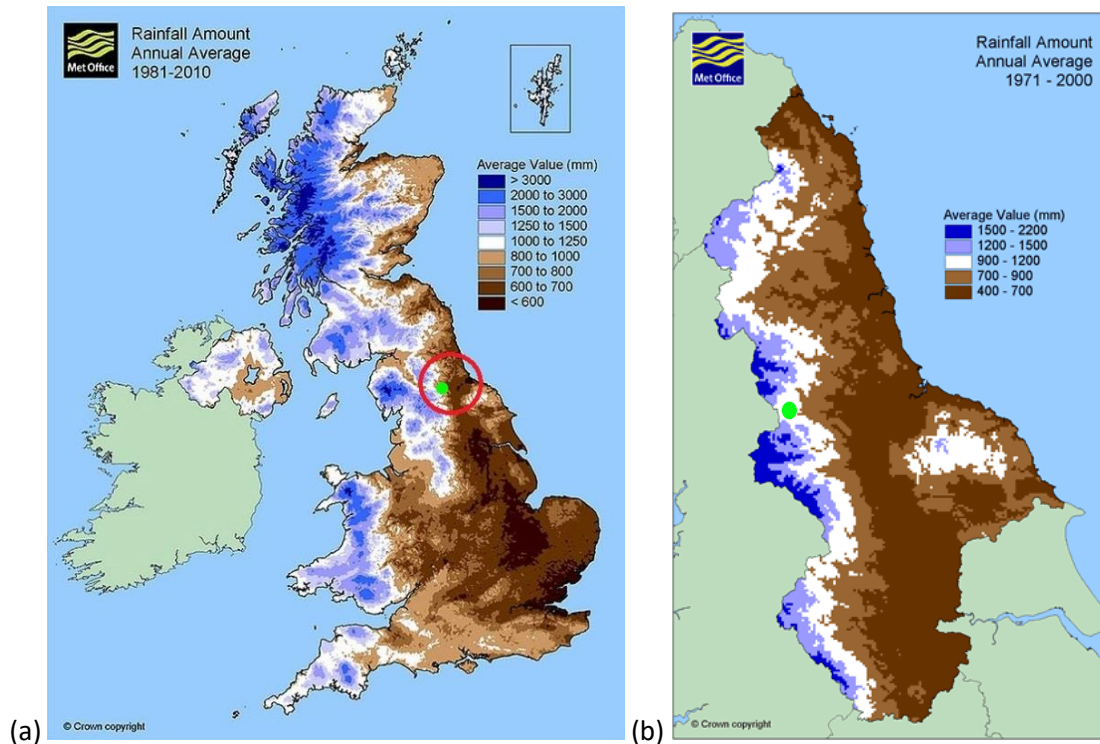
Figure 3.2 **Maps showing *(a)* UK average rainfall. The red circle shows the approximate boundary of the Tees catchment and the green point indicates the approximate location of the Tutta Beck catchment (1981–2010); *(b)* average rainfall in the north-east region. The green dot indicates the approximate location of the Tutta Beck catchment (1971–2000) (Met Office, 2016).**

The tipping bucket rain gauge at Brignall (src_id-2009, Station Code-RAIN 028904, NZ 069123) was used to represent rainfall for the catchment, as it is the only gauge here.

Return period analysis is not an aim of this thesis; however, it gives an indication of rainfall severity for 2015 (Figure 3.3). Data from the FEH is displayed in Figure 3.4 and suggest 2015 events fell within the 1 in 1- and 1 in 100-year return period. The values from the FEH represent a 24-hour moving window, whereas the totals in Figure 3.3 are from a fixed daily window.
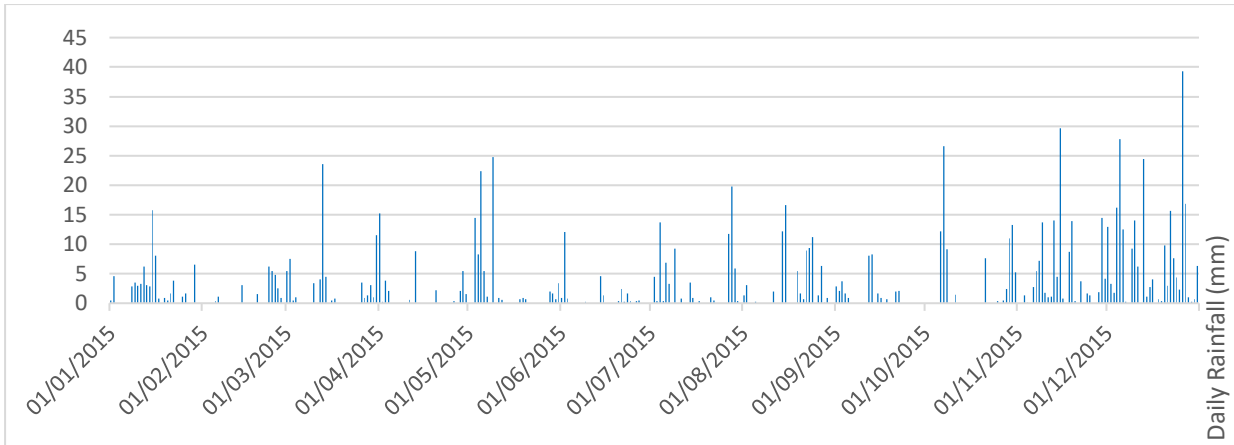
Figure 3.3 Graph showing daily observed rainfall for the Brignall rain gauge. Note: There are three missing results for the latter period of the year (November and December).
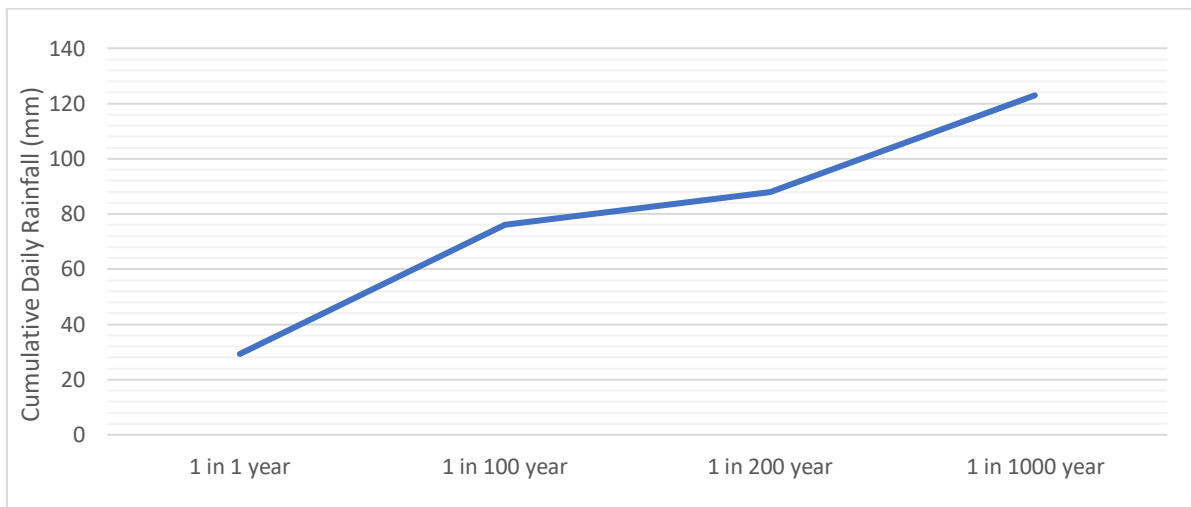
Figure 3.4 Graph showing the return period analysis for rainfall in the Tutta Beck catchment. Twenty-four-hour rainfall totals (taken from the FEH) are displayed.

3.2.2   Topography

The catchment is situated in the eastern Pennines and elevations range from 311m AOD in the west to 124m AOD at Greta Bridge (Figure 3.5). The greatest elevations (Figure 3.5) and gradients (Figure 3.6) are towards the hard rock outcrop to the west of the catchment (Figure 3.7).
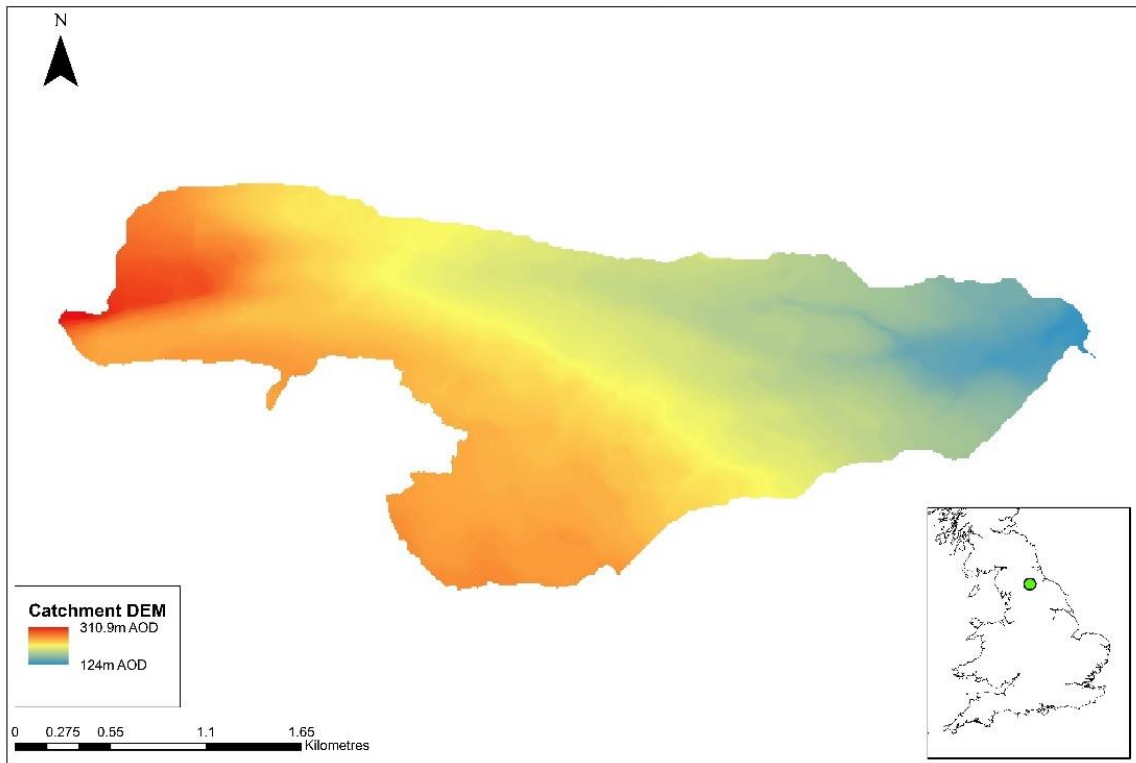
Figure 3.5 **DEM of the Tutta Beck catchment.**
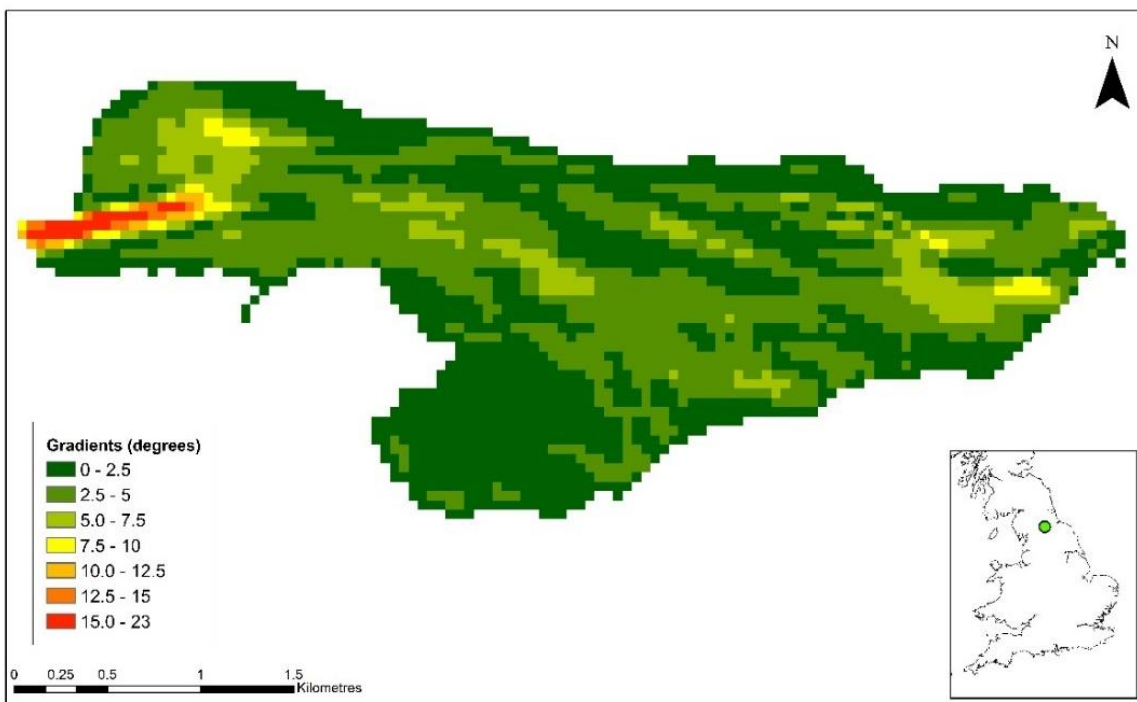
Figure 3.6 **Map showing slopes across the Tutta Beck catchment.**

3.2.3   Basal geology

The basal geology is banded east–west and there are four bedrock classes (Figure 3.7): limestone,

sandstone, siltstone and mudstone (Alston Formation); sandstone (Alston Formation); limestone

(Four Fathom Limestone Member); and limestone (Greater Limestone Member). The higher

elevations in the catchment are identified as being strongly bound with infiltration through

discontinuities; otherwise, throughflow is low (BGS, 2017). The watercourse aligns with the east–

west-orientated bedrock bands, which are probably associated with weaknesses at bedrock joints

(BGS, 2017).
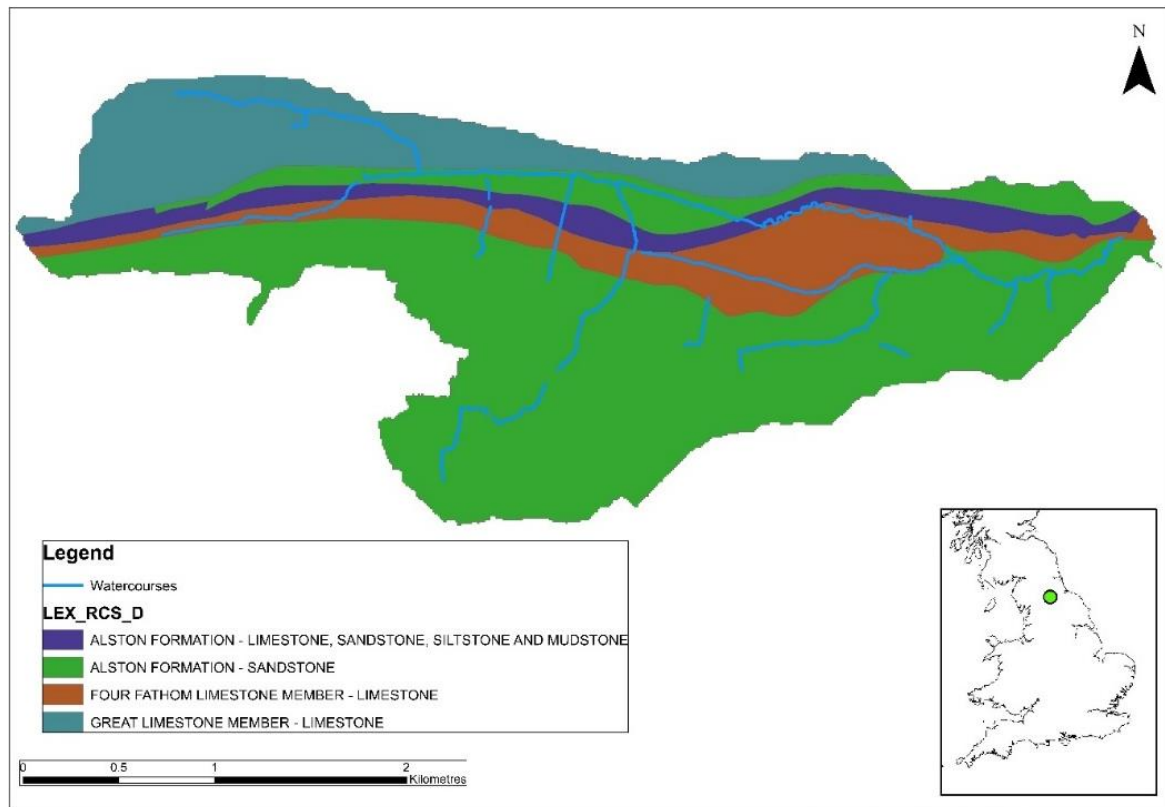
***Figure 3.7* Map showing basal geology of the Tutta Beck catchment (reproduced with the
permission of the British Geological Survey ©NERC. All rights reserved).**

3.2.4   Superficial geology

Superficial geology is predominantly glacial till of the Devensian–Diamicton type (Figure 3.8),

typically with low infiltration capacity (BGS, 2017). Near the watercourse there are deposits of

alluvium and river terrace deposits (Figure 3.8). Because such deposits are associated with

modification through fluvial processes and are predominantly located in floodplain areas, they

typically form loosely bound soil with a high capacity for infiltration.
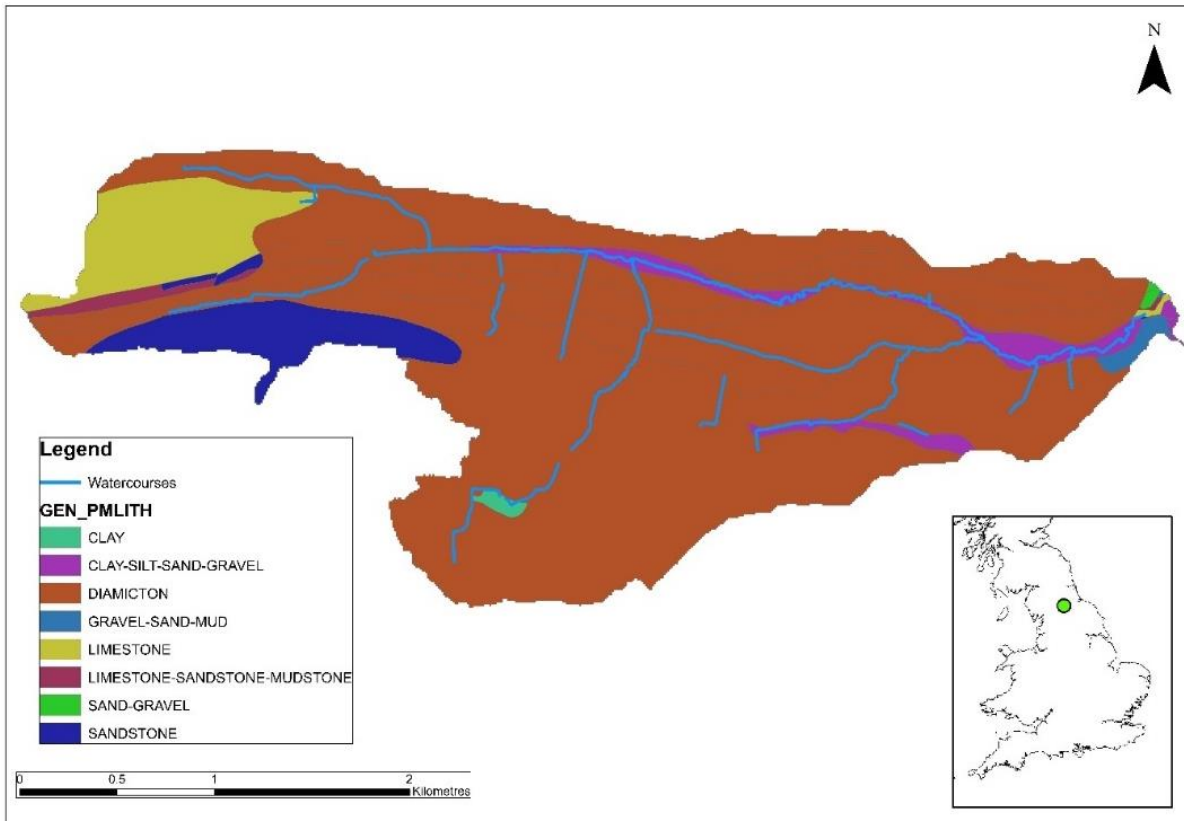
Figure 3.8 **Map showing superficial geology of the Tutta Beck catchment (reproduced with the permission of the British Geological Survey ©NERC. All rights reserved).**

3.2.5   Soils

There are three dominant soil classes in the catchment (Figure 3.9). Most of the catchment consists of freely draining, slightly acidic loamy soil (Cranfield Soil and Agrifood Institute, 2015) suggesting infiltration would be high. The south-west of the catchment is classed as having slowly permeable, seasonally wet, loamy and clayey soils with impeded drainage (Cranfield Soil and Agrifood Institute, 2015), suggesting susceptibility to overland flow. To the north-west there is a small outcrop of freely draining, slightly acid, but base-rich soil (Cranfield Soil and Agrifood Institute, 2015), suggesting infiltration should be high. These classes would suggest there is good infiltration capacity in the catchment's soils with a reduced likelihood of overland flow.
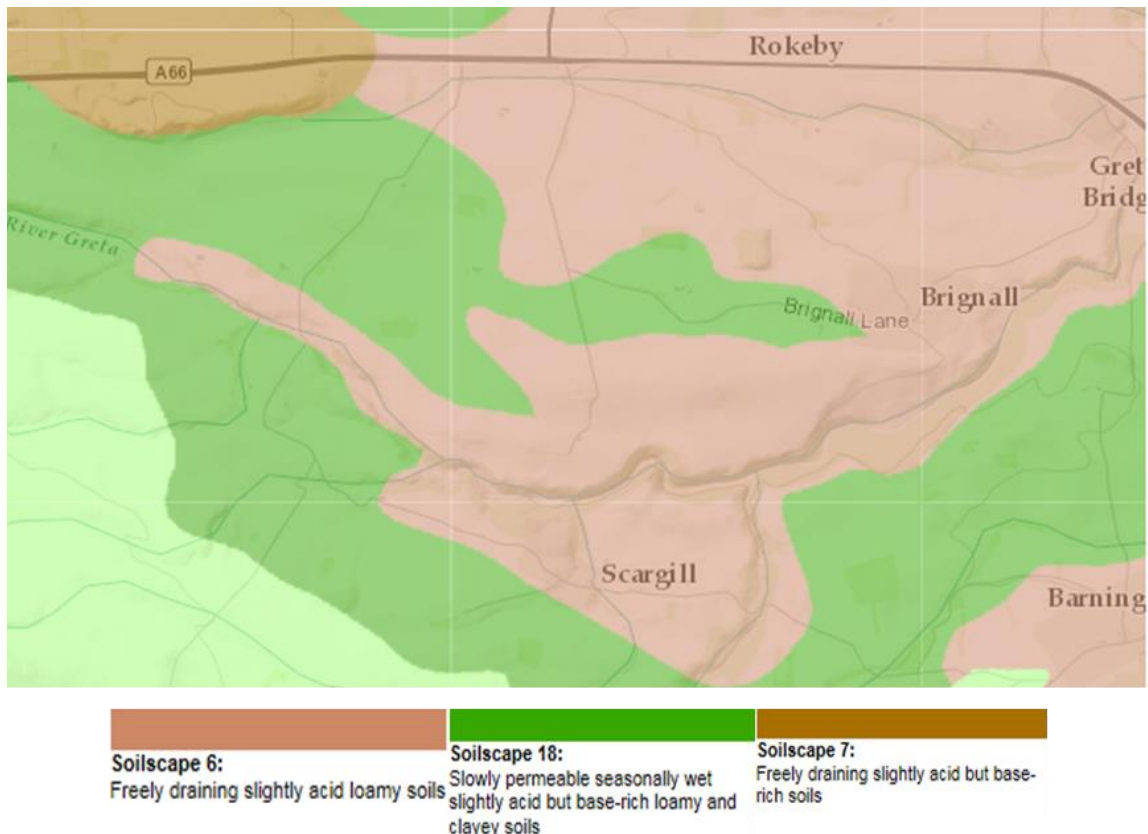
Figure 3.9 **Map showing soil types across the Tutta Beck catchment (Cranfield Soil and Agrifood Institute, 2015).**

3.3   Human influences

The area around Greta Bridge has been occupied since the second century (Historic England, 2000), when the Roman fort was established. Without this there would be a very different hydrological regime. The catchment has been used for agriculture and quarrying and this section introduces human factors and associated challenges.

3.3.1   Land use

Agriculture is the dominant land use in the catchment, the west being largely improved grassland, the east mainly arable land (Figure 3.10). These land uses are common throughout this area of the Tees catchment. The high agricultural potential and value is the primary reason why there are so few other land uses throughout the catchment.

Figure 3.10 Map showing land cover in the Tutta Beck catchment (based on CEH land cover map 2007).

The classes displayed in Figure 3.10 show a range of landcover classes, for the purposes of this research these have been simplified to those displayed in Table 3.1 where Acid grassland, Heather grassland and Rough grassland are all combined within a new Rough grassland classification.

Table 3.1 Land cover data for the Tutta Beck catchment, the total catchment size being 706.25ha

Land cover value	Land cover	Percentage cover	Land take (ha)
1	Broadleaf/deciduous woodland	3.38%	25.25
2	Coniferous woodland	0.85%	60
3	Arable and horticultural	27.79%	212.25
4	Improved grassland	56.72%	394.5
5	Rough grassland	9.65%	60.25
6	Developed areas	1.6%	8

3.3.1.1 Agriculture

The oldest maps available (*c*.1856) show the catchment has historically been agricultural and since this time many field boundaries have been lost to create larger fields. Field visits found examples of management that could increase runoff, such as downslope running trackways with vehicle movement occurring over saturated soils (Figure 3.11).

Figure 3.11 **Image showing downslope traffic across the catchment and also deep and pronounced tyre rutting (author, 19 April 2016).**

There are limitations with regard to using tractors across slopes because the high centre of gravity means there is a risk of machinery toppling over when running across slope, resulting in travel with the slope for safety (Eather & Fraggar, 2009). The tyre rutting displayed in Figure 3.11 also shows the impact that trafficking across saturated soils can have. At the bottom of Figure 3.11 the right-hand tyre rut shows a ridge of pushed over soil from the tractor sliding sideways, if this were to happen while running across the slope then the risk of toppling would be greater when the tractor regained grip. Another example of soil damage is repeated trafficking over saturated areas (Figure 3.12). Here, soil structure is lost, and when dry the soil will become compacted, preventing infiltration.

Figure 3.12 Image showing tyre rutting and soil saturation through a gateway at the bottom of an agricultural field in the Tutta Beck catchment (author, 19 April 2016).

3.3.1.2   Associated development

Throughout the catchment, impermeable surfaces have expanded, a result of tarmac roads have increased conveyance, as shown in Figure 3.13 on Brignall Lane. There are 12 farms throughout the Tutta Beck catchment and historic mapping shows that most farm complexes have expanded significantly with no evidence of techniques to mitigate increased runoff because of the increase in impermeable area.
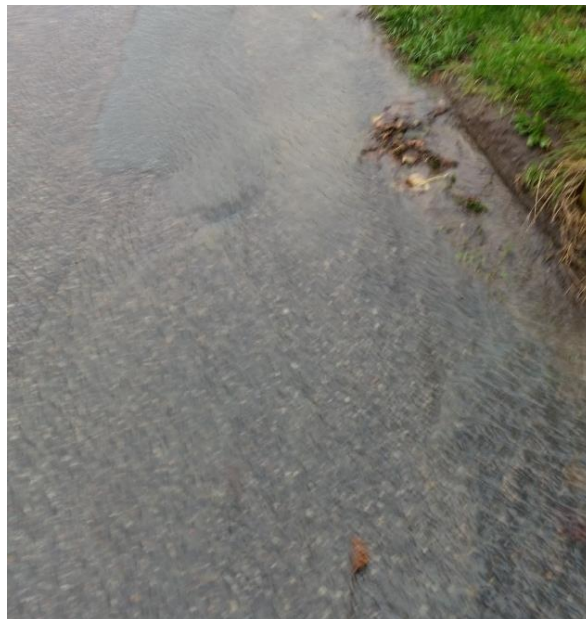
Figure 3.13 Image showing water flowing downslope on Brignall Lane from field visit (author, 5 December 2016).

Kilmond Wood Quarry to the north-west of the catchment requires pumping to create a dry working area in the excavation, Alstead (2013) identified these pumps discharge into Tutta Beck; however, this was not validated as part of this study.

3.3.2   Heritage designation

In the lower catchment, a Roman fort with scheduled monument status as well as listed buildings restrict possible flood risk reduction works. Alongside public opinion, these designations prevented the proposed conventional protection strategy of a flood fence. The designations are mapped in Figure 3.14.
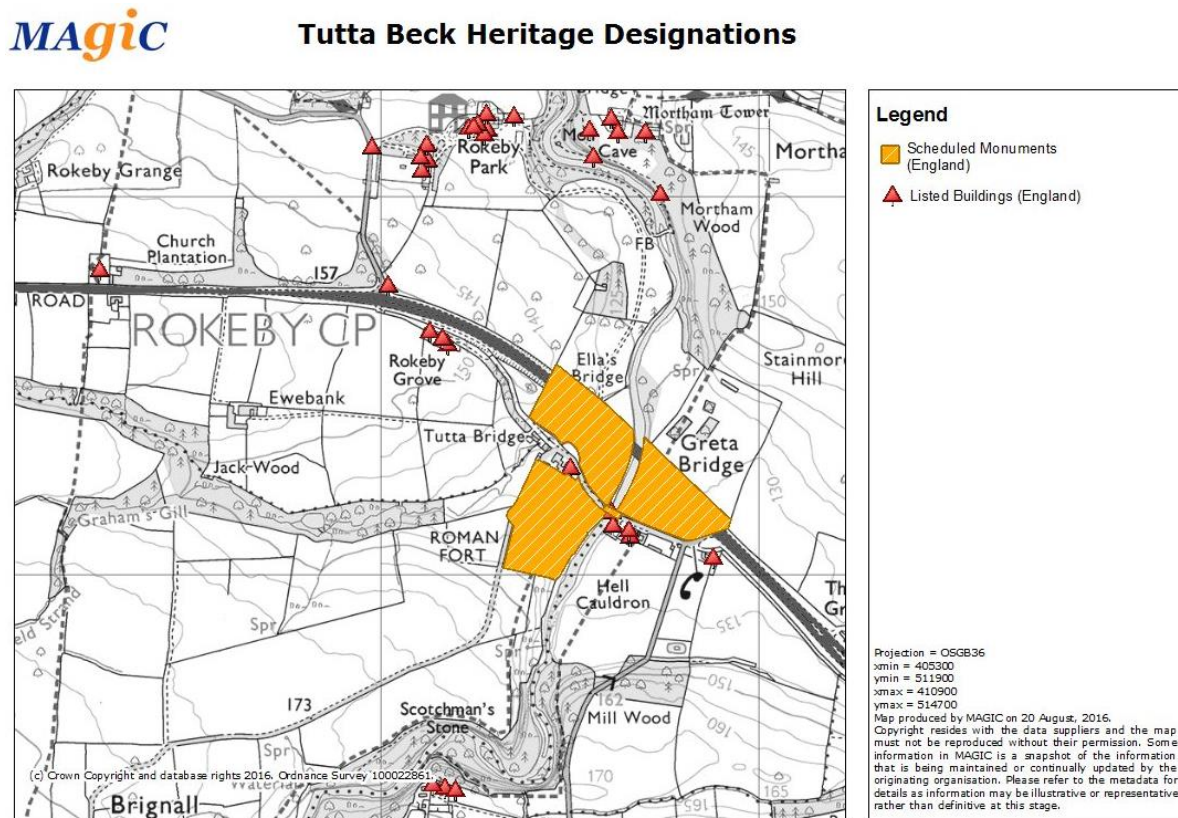
Figure 3.14 **Map showing heritage designations in the Tutta Beck catchment.**

One of the protected walls downstream of the bridge has a blocked-up archway that could be reopened to reduce the bottleneck effect on the channel in this area.

3.4   Flooding in the Tutta Beck catchment

A key flooding event occurring in April 2012 when three properties adjacent to a canalised section were flooded (Alstead, 2013, Longstaff, 2015). This was the first recorded flood incident and was followed by another similar event. Both supported the justification for this research project.

Figure 3.15 and Figure 3.16 show there are a number of issues with regard to the properties. Two significant directional changes (shown by white arrows in Figure 3.15) entering the canalised section adjacent to the properties mean it is likely that the channel overflows due to momentum rather than capacity (blue arrow in Figure 3.15). The canalised section is poorly maintained blockwork with vegetation growth and it discharges through a dual-span culvert bridge (Figure 3.16), downstream of which is a further 90° directional change.
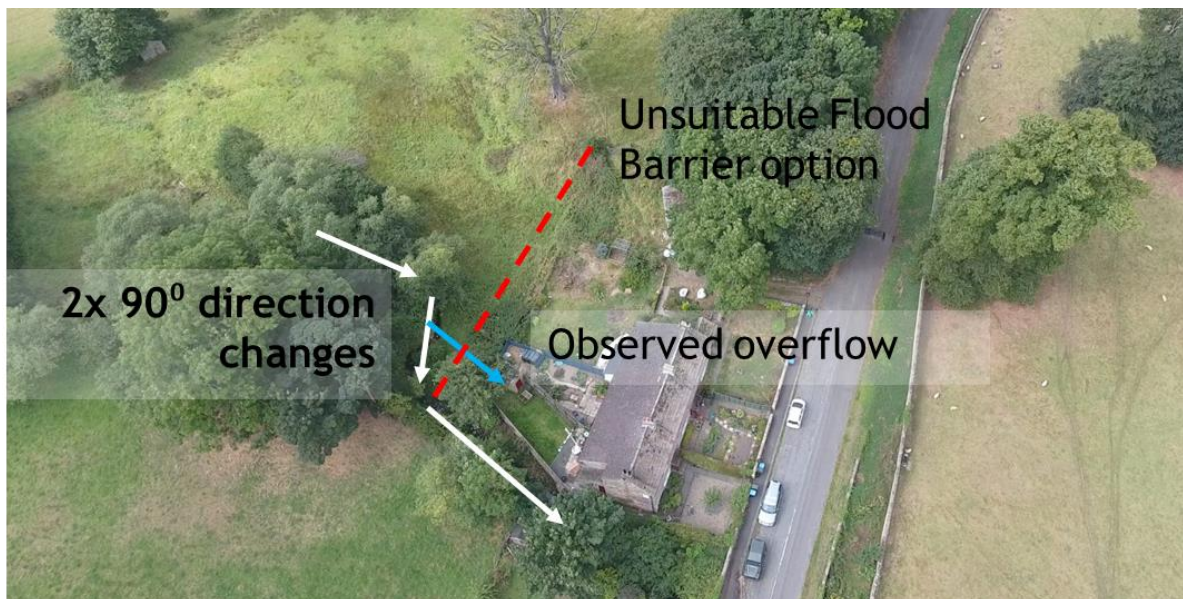
Figure 3.15 **Aerial image looking down over the properties in a westerly direction.**

Figure 3.16 **Aerial image looking down over the properties in a southerly direction.**

Tutta Beck is a gravel bed river with a 'flashy' flow regime typical of watercourses in this area of the catchment. Table 3.2 shows the flooding history and comments from field observations. The initial study by Alstead (2013) made several comments about the catchment and about conditions with regard to flooding. First, to generate flooding without a blockage the discharge needed to be in the region of $12m^3s^{-1}$. However, comments in Alstead (2013) and observations during 2015 suggest out-of-bank flow upstream of the cottages could pose a risk of flooding at lower discharge rates. Second, the events that resulted in internal flooding of the receptor were low-return period events. Using the FEH model, Alstead (2013) had to simulate 75% runoff throughout the catchment to generate flooding at the properties. This supports claims from stakeholders that flooding was caused by catchment saturation rather than the volume of rain during an event.

Table 3.2 **Recent flood history in the Tutta Beck catchment and other events significant for hydrology**

Date	Event
26/04/2012	Fence crossing Tutta Beck entrained debris, attenuating large volumes of water. Failure resulted in outburst flooding at the properties.
28/06/2012	Western arch of bridge blocked by the oil tank serving the three cottages that broke free and became wedged within the arch (Alstead, 2013).
01/2013	Sediment accumulation in culvert bridge becoming vegetated. Foul sewerage pipe passes through arch entraining debris and reducing capacity (Alstead, 2013).
17/05/2015	Where Tutta Beck flows through woodland further upstream of receptors, several informal debris dams impound water. When these barriers fail a surge/outburst flood could resulting in flooding downstream, as in the April 2012 event.
05/12/2015	Storm Desmond – flow and rack marks show flow was close to garden where wall would impound flows. Out-of-bank flows driven by momentum appear to be a greater risk than capacity issues.
06/12/2015	Water gate under Roman wall entrained debris, causing it to back up.
09/01/2016	Survey of culvert bridge shows bridge buttress restricts entry into eastern span to 1.2m. Each span is 2.7m, which means the eastern span is restricted to less than 50% capacity.

3.5   Summary

The key considerations in the catchment are the land use and the need for the catchment to maintain its function beyond the introduction of the FAS. It is the agricultural function that is probably a significant contributor to the flood risk at the receptor. Poor management at the receptor could significantly increase flood risk, highlighted by the blockages and the out-of-bank events caused by the significant changes in direction. The statutory heritage designations pose another challenge for the development of the FAS, which means that interventions should not be inserted here unless they are to have minimal visual impact.

Chapter 4   Methodology

4.1 Introduction

This chapter outlines the methods used to answer the research aim and objectives. Figure 4.1 provides a conceptual structure of the research process.
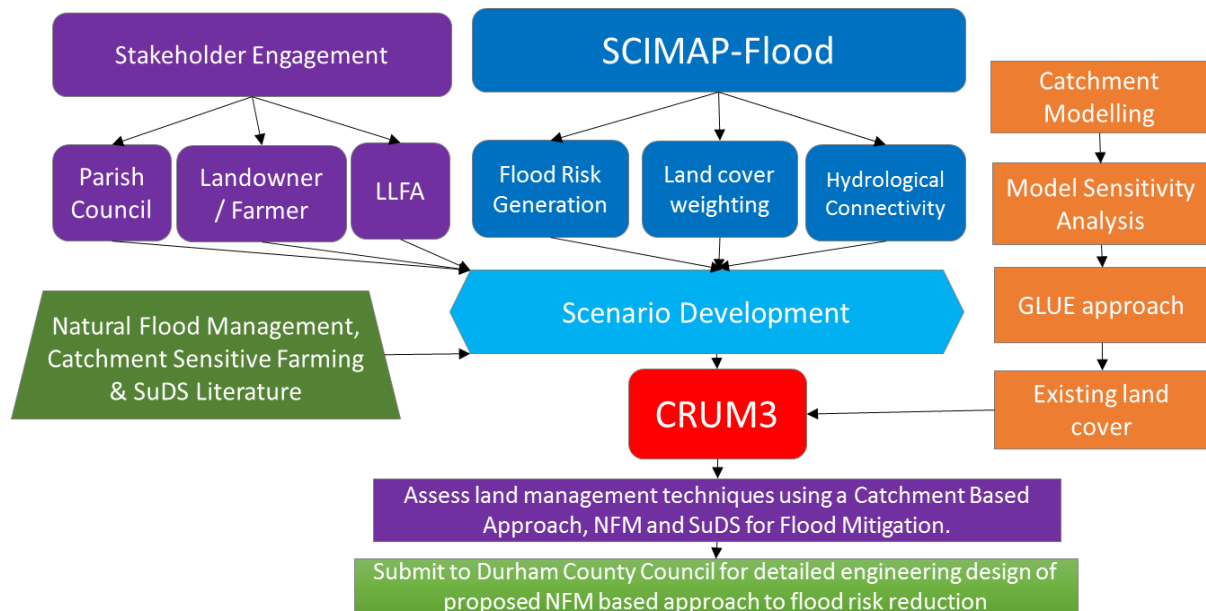
Figure 4.1 **Flow diagram of thesis structure for delivering research aims (Fraser, 2017).**

4.2 Generating catchment datasets

To run modelling and perform catchment-scale data analysis it is important to have complete catchment coverage and complete datasets. This section and its subsections outline approaches used to generate complete datasets for modelling and data analysis.

4.2.1 Catchment delineation

Delineating the catchment is best performed using the highest resolution topographic information that captures features influencing flow routing. Figure 4.2 shows the delineated Tutta Beck catchment based on the 5m and 10m elevation datasets. Looking at Area 1 in the catchment, the watercourse draining this is routed through a road culvert, and the higher 5m dataset identifies this as a barrier to flow routing. Area 2 is not in the Tutta Beck catchment because drainage has been dug that drains the area into a different catchment (River Greta).
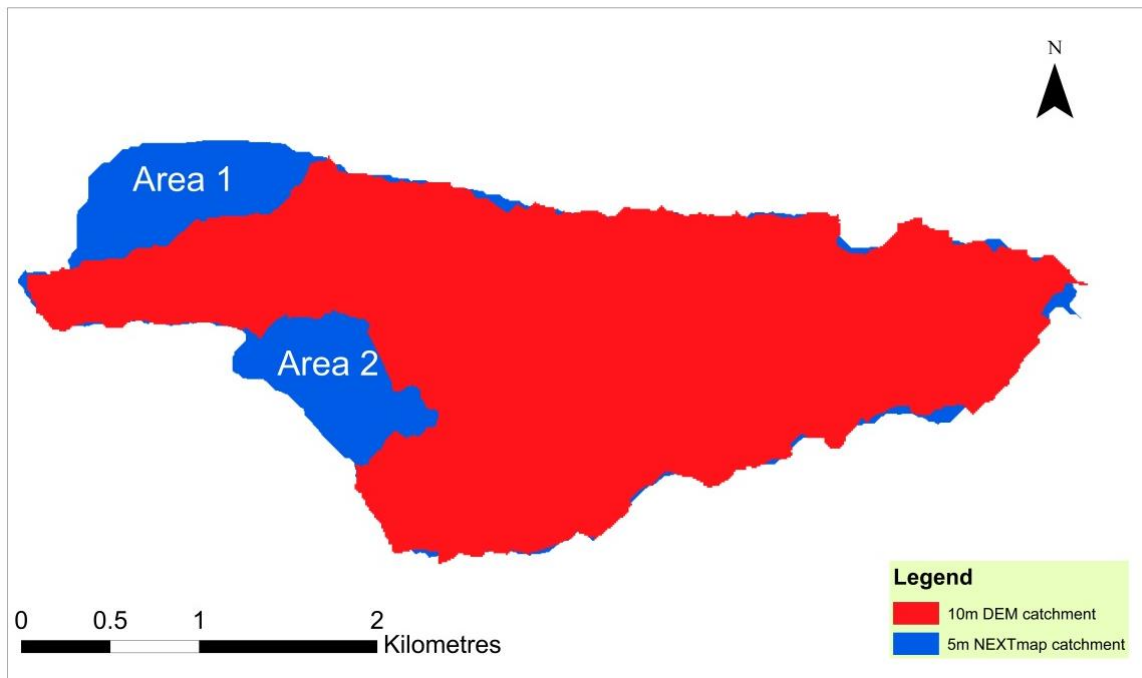
Figure 4.2 **Map showing catchment outlines defined from different data sources.**

Area 2 was removed from the 5m delineated catchment using the EA's LiDAR data available for the

area. This was done by delineating the sub-catchment and then clipping the 5m delineated Tutta

Beck catchment (Figure 4.3).
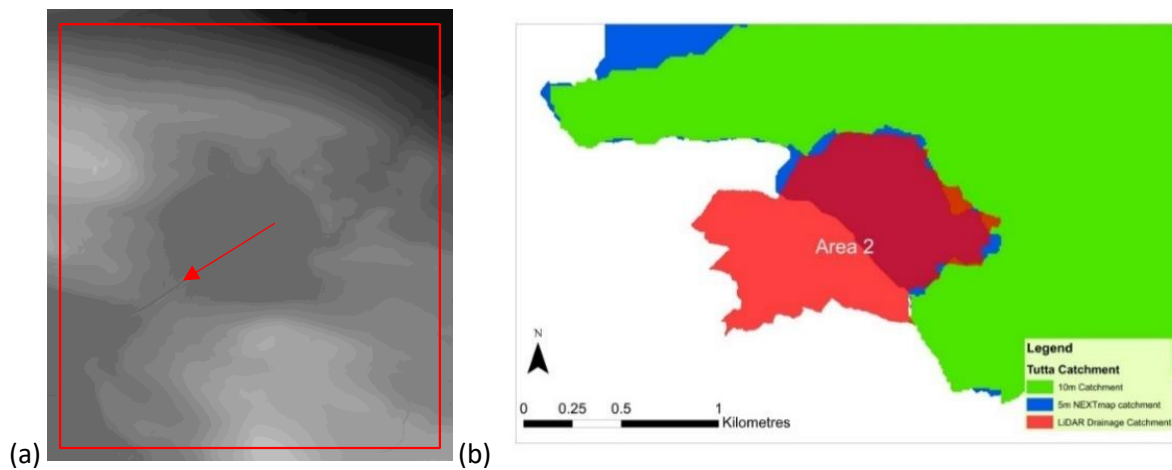
Figure 4.3 (a) **Deeper drainage ditches;** *(b)* **Map showing area artificially drained across the watershed.**

4.2.2   Discharge dataset

Flood risk in the Tutta Beck catchment is associated with high flows overwhelming the channel;

therefore, appraising the impact of interventions on peak discharge is the best measure. This

required discharge data for the catchment, which was captured using a pressure transducer water

level logger. The model was a TD-Diver with a 10-metre range and an accuracy of ±0.05mm with a

resolution of 0.0006m. The diver provided depth data at 15-minute intervals as shown in Figure 4.5, performing flow monitoring throughout the year at different stage depths (Figure 4.4). As a result, a stage–discharge relationship can be constructed, as in Figure 4.6. The relationship is non-linear, and research by Owen (2016) demonstrated that this relationship could be used to infer discharge using prolonged depth datasets (Figure 4.5).
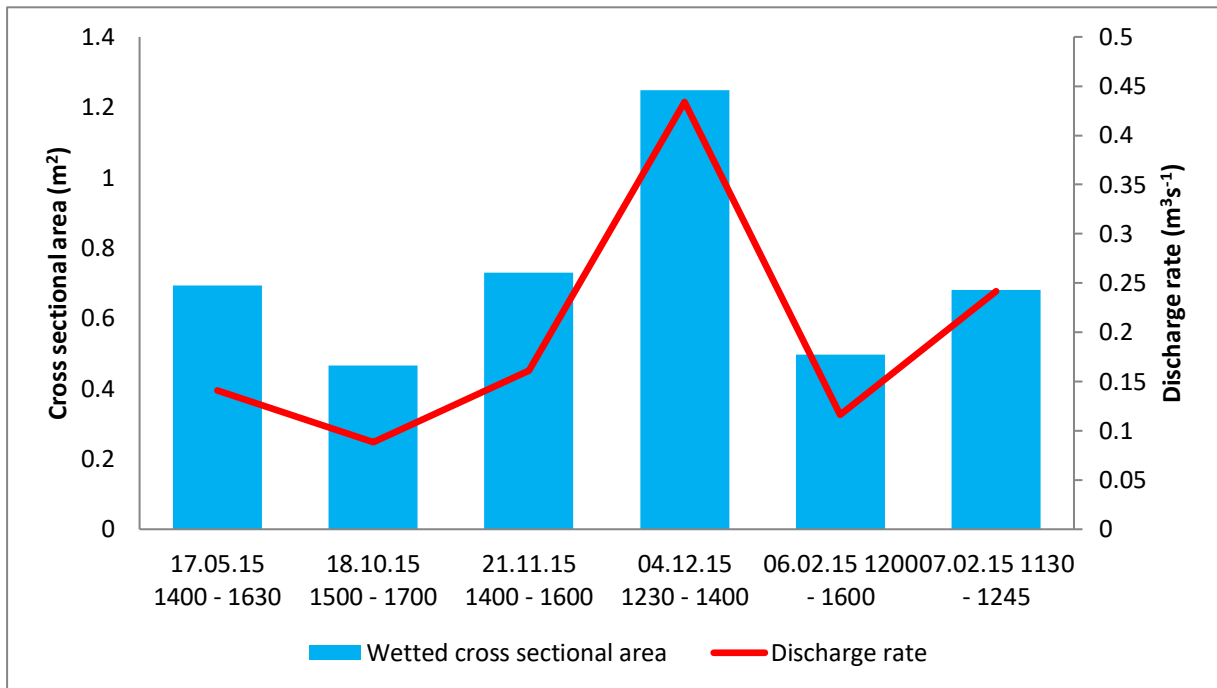
Figure 4.4 **Graph showing the cross-sectional area and discharge during the observation period.**
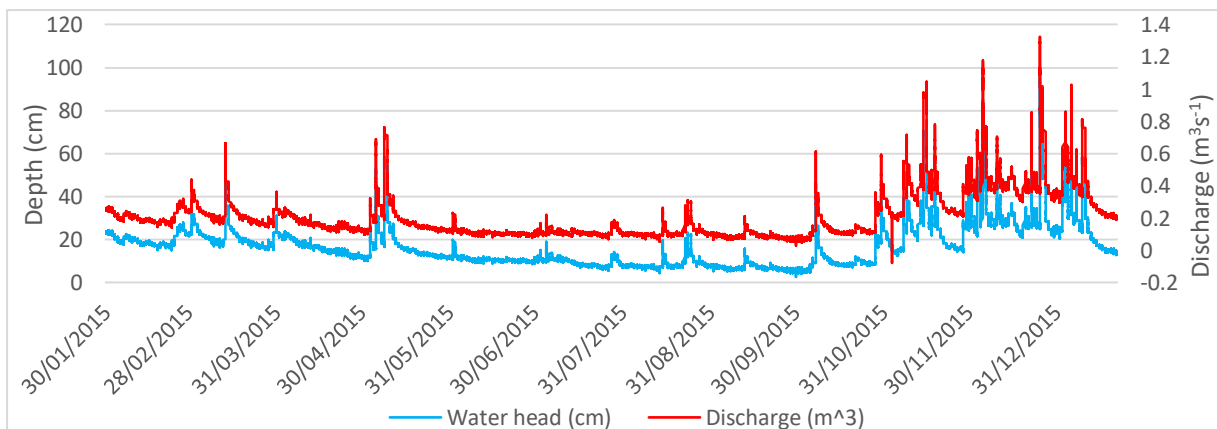
Figure 4.5 **Graph showing the simplified depth–discharge relationship for the period of observation.**

The discharge data for this research was produced using a power rating curve and the fitted model is described in Equation 1. This model fitted observed data with an R^2 value of 0.99 and Figure 4.6 shows the power rating curve used to generate discharge from depth data.

$$Q = 0.93724S^{2.5358}$$

Q is the discharge in m³s⁻¹
S is the stage in metres

y = 9.3724x²·⁵³⁵⁸
R² = 0.9916
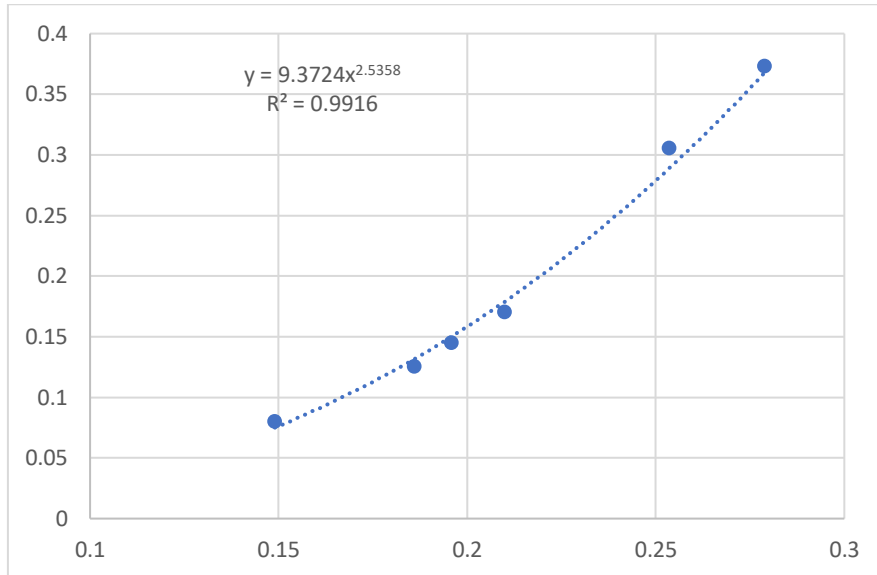
Figure 4.6 **Graph showing the power rating curve for the stage–discharge relationship.**

4.2.3   Infiltration testing

The geology and soils across the catchment have the potential for a spatially variable response to rainfall. As a result, it was important to perform infiltration testing to consider soil type and land use. Testing used a Decagon Devices minidisc infiltrometer, targeted at arable and improved grassland land covers with consideration of soil and geology datasets. Figure 4.7 shows average infiltration rates were higher on improved grassland fields than arable land. Observations showed infiltration had high spatial variation, ranging from 264mmhr⁻¹-24mmhr⁻¹ for improved grassland and from 240mmhr⁻¹-12mmhr⁻¹ for arable land. The averages and ranges were based on 50 infiltrometer results collected over 5 days.
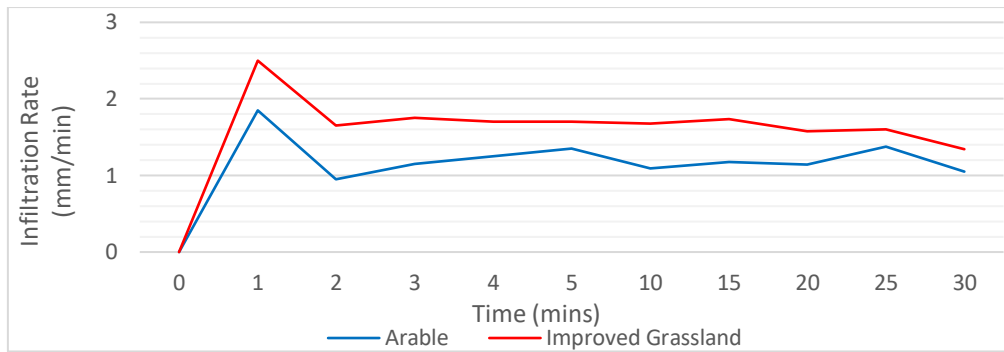
Figure 4.7 **Graph showing infiltration rates for improved grassland and arable land cover.**

4.3   Stakeholder engagement

To develop scenarios and support development of the FAS, local stakeholders were engaged. Stakeholders included the Tees Rivers Trust, Durham County Council, the landowner's land agent, the parish council and local farmers.

Meetings were held to discuss the techniques and locations suitable for interventions as well as areas identified as contributing to runoff. Initial meetings were conducted before catchment analysis was performed to prevent bias in discussions. Feedback from stakeholders identified suitable areas for interventions (Figure 4.8), which could include, but are not limited to, LWD, attenuation and land cover change. Discussions showed a preference for physical structures to mitigate flood risk, such as LWD and attenuation. Concern was expressed by all over the use of infiltration improvements and land cover change for flood alleviation, specifically with regard to accessing funding and the impact on agricultural function.

Following SCIMAP-Flood analysis further meetings were held to interrogate outputs and discuss both alternative funding sources and whether or not further areas could be included in the FAS. These funding sources expanded the area of investigation and introduced interventions outside the FAS. This is captured in Figure 4.8 by the land cover change and incorporation of the swales in the lower catchment.
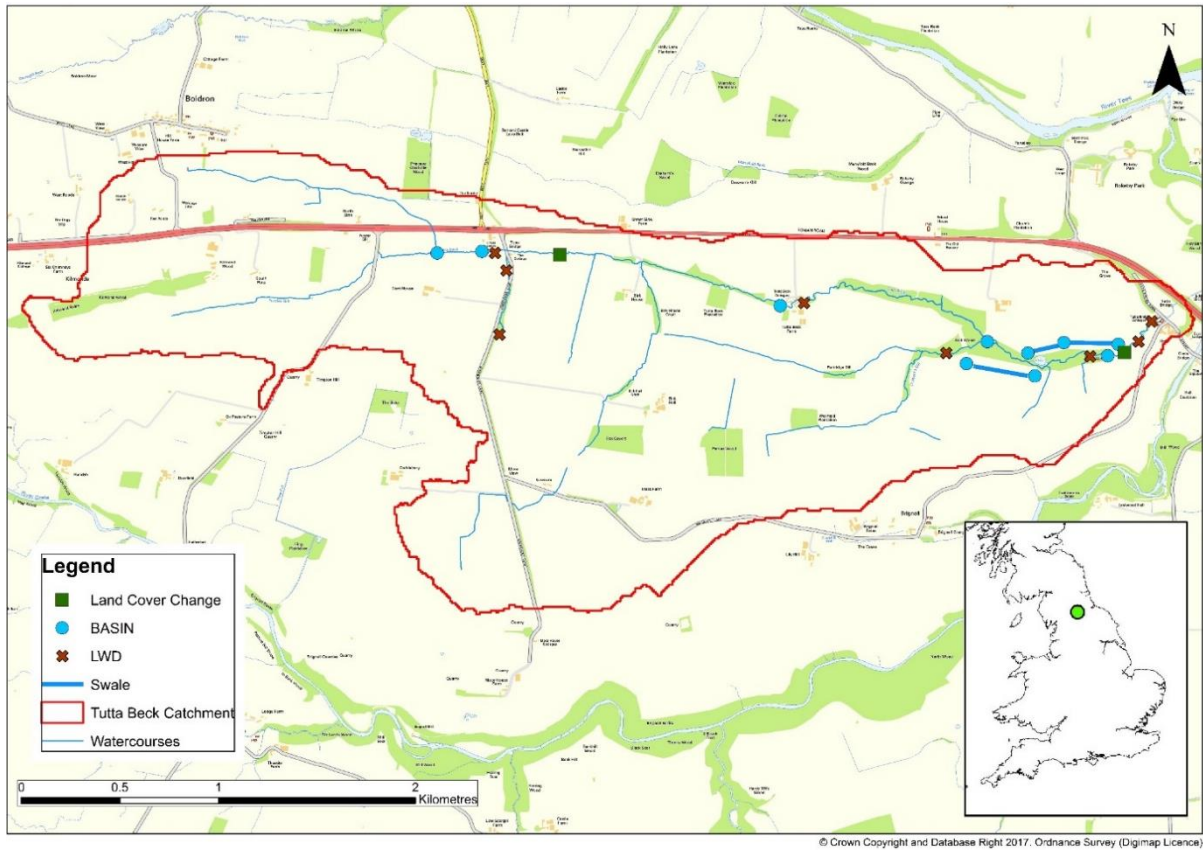
Figure 4.8 **Map showing locations identified as suitable for NFM techniques.**

4.4   Risk mapping approach

Risk mapping is a process in which the factors contributing to risk are considered at the point scale using spatial analysis and then used to generate a map of risk ratings on a wider scale. Figure 4.9 shows a simple risk map that considers the spatially distributed risk of land cover and slope to produce a combined risk map. This does not include weightings and, therefore, is purely to demonstrate the concept.

(a)

(b)

(c)
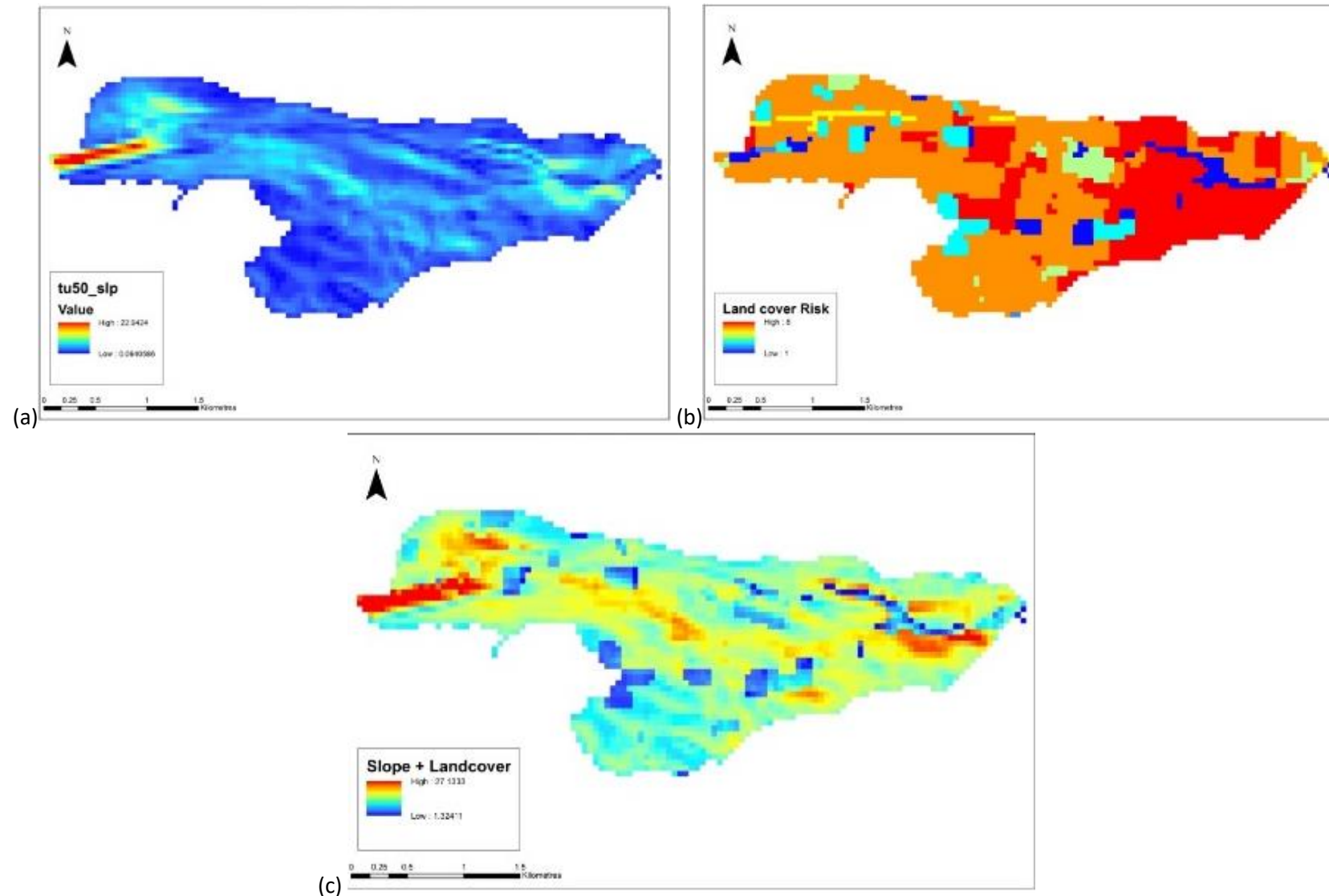
Figure 4.9 (a) **Map showing slope risk across the Tutta Beck catchment;** *(b)* **Map showing land cover risk across the Tutta Beck catchment;** *(c)* **The two maps combined to show slope and land cover risk across the Tutta Beck catchment.**

4.4.1   SCIMAP-Flood

Flood risk is a new function added to the SCIMAP diffuse pollution risk model (Reaney et al., 2011b).

SCIMAP was used in Lane et al. (2009) to identify diffuse and discrete pollution sources and it

considers the likelihood of soil eroding and the potential for overland flow to entrain soil and

transport it to a channel. The processes linked to diffuse pollution are synonymous with those used

to drive flood risk (Fraser & Reaney, 2018). The mapping does not consider flood volumes but

provides a powerful tool for informing investigation, supporting fieldwork and assessing hydrological

connectivity at the catchment scale.

The approach taken in SCIMAP-Flood is to identify critical source areas generating potential flood

waters and a hydrologically connected pathway to the river system. Figure 4.10 shows the SCIMAP

conceptual model. The flood risk generation index is derived from land cover and local topographic

conditions, with risk weightings. The network index (Lane et al., 2009) is derived from the

topographic routing and spatially variable rainfall volumes. These combine to generate a spatially

variable risk score for locations throughout the catchment.
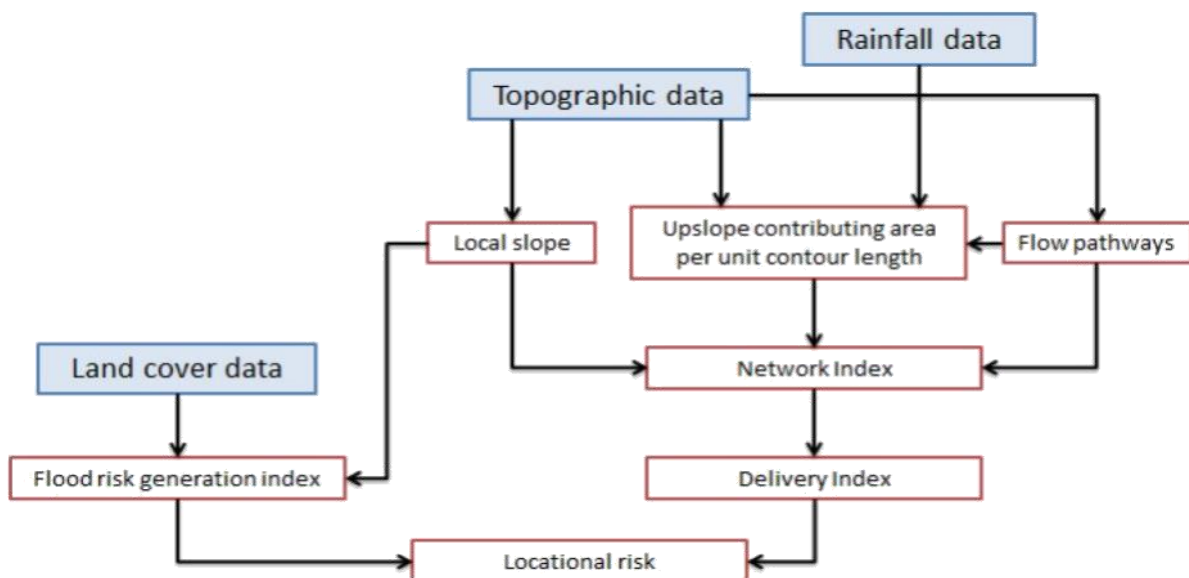
Figure 4.10 **SCIMAP-Flood conceptual model showing the two processes of network risk and
generation risk and how they are combined to provide a locational risk (Pearson, 2016).**

4.4.2   Data requirements

To generate the risk map, SCIMAP-Flood requires four catchment datasets: DEM, land cover map (LCM), rainfall data and watercourses/channels. Using this process, Figure 4.11 was developed to identify the areas of greatest risk across the catchment.
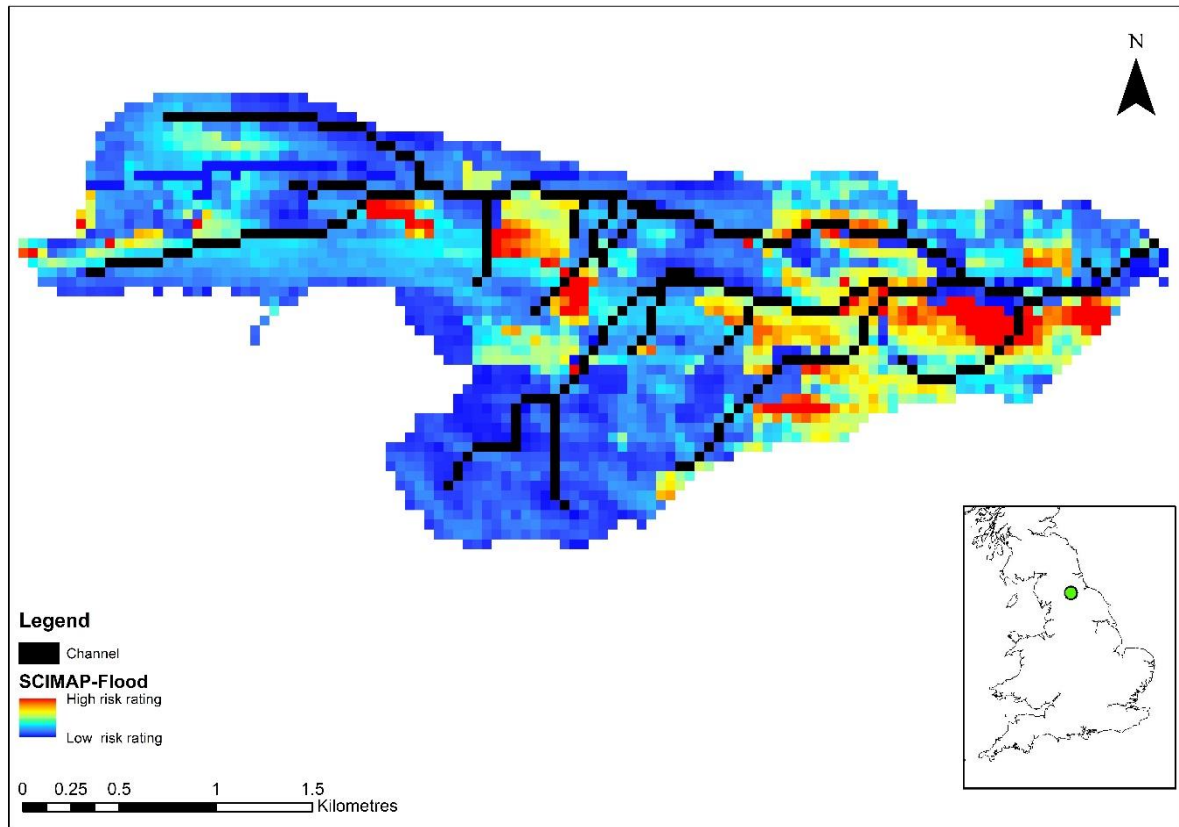
Figure 4.11 **SCIMAP-Flood risk map for the Tutta Beck catchment.**

4.5   Hydrological model choice

CRUM3 (Lane et al.*, 2009) was selected for this study to investigate mitigation techniques including land use change, flow restrictions and topographic manipulation. CRUM3 has been applied in academic, government and industrial projects throughout Northern England, including: the River Eden and Dacre Beck in Cumbria (Pattison, 2010; Smith, 2012; Pearson, 2016); and the River Rye in North Yorkshire (Lane et al.*, 2009). The relative proximity of these projects to Tutta Beck and their catchment similarities mean the model is suitable for use in this study.

CRUM3 represents the essential catchment hydrological processes and produces detailed outputs with minimal data requirements (Lane et al., 2009). CRUM3 uses fewer parameters and datasets when compared to similar fully distributed models such as MIKE SHE/MIKE 11 (Thompson et al., 2004).

4.6   CRUM3

CRUM3 is a physically based, fully spatially distributed simulation of catchment hydrology and was developed in C++ by Dr Sim Reaney of Durham University. CRUM3 requires minimal parameters and datasets, making it suitable for simulating many data-sparse UK catchments. The model was developed to assess the impacts of climate change and land management on hydrological extremes and water quality (Lane et al., 2009; Smith, 2012). The use of a stochastic weather generator within CRUM3 enables the natural variability of storm events to be simulated from daily data at 15-minute intervals. The use of high-performance computing at Durham University facilitated the GLUE approach, which assesses different combinations of parameter sets, to be used in simulations and capture uncertainty.

4.6.1   Structure of CRUM3

CRUM3 is constructed based on four modules: weather, hydrology, landscape and river network. These are shown in Figure 4.12.
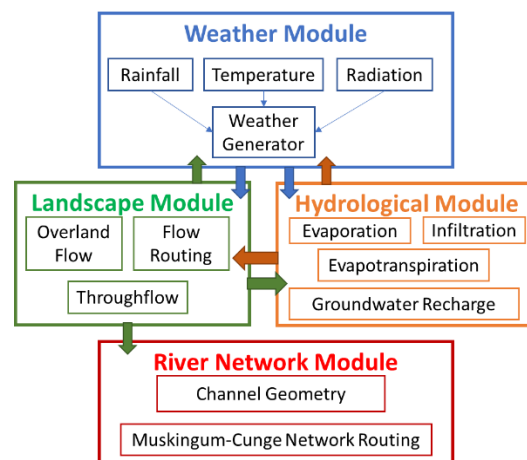
Figure 4.12 **Structural representation of CRUM3 model (from Smith, 2012).**

Details of the structure and equations driving CRUM3 can be found in Appendix 1.

4.6.2   Data requirements

CRUM3 requires weather, flow and spatial datasets, with discharge data being used to validate the model.

The weather data required for CRUM3 is diurnal maximum and minimum temperatures and daily precipitation. An appraisal of available rainfall datasets identified both a Highways England weather station at North Bitts Farm and a Met Office rain gauge at Brignall (Met Office station code – RAIN 028904, NZ 069123). The Highways England station uses a 10-minute time series; however, significant missing data and lack of a prolonged dataset meant this could not be used.

The channel discharge data used to validate the CRUM3 output is from an in-situ pressure transducer (Van Essen Instruments) that records level data at 15-minute intervals. There are a range of datasets available from rain gauges throughout the wider area, this is available from Met Office datasets and include gauges at Barnard Castle, Forcett, Richmond and Raby Castle.

The topographic dataset for the catchment is delineated from a 10m dataset. Smaller datasets had inaccuracies and LiDAR was incomplete (see Section 4.2.1).

This catchment had not been monitored prior to the study (other than the Brignall rain gauge). Therefore, only the years 2015 and early 2016 were selected for simulation due to availability of catchment monitoring for validation. There was no flooding observed during this period meaning conditions that triggered a flood incident were not recorded and should not be found through simulations.

4.6.2.1   Generating the rainfall dataset

Hydrological models require full rainfall datasets for the period of observation and simulation (Hasan & Croke, 2013), and in many cases datasets are incomplete (Gyau-Boakye & Schultz, 1994; Di Piazza et al., 2011). The CRUM3 model requires a similar full rainfall dataset, which was not available for Tutta Beck. There are typically two approaches to manage this: avoiding the missing timeframe by

selecting a different window; and removing data gaps to create a continuous record. However, these approaches waste data and limit simulation accuracy (Di Piazza et al., 2011). CRUM3 requires a full rainfall dataset to accurately represent antecedent conditions. Therefore, a different approach is required, namely, to populate the dataset where there are missing values. The methods investigated for doing this were: normalised difference (see Section 4.6.2.1.1); inverse distance weighting (IDW) (see Section 4.6.2.1.2); and the distance power method (see Section 4.6.2.1.3).

4.6.2.1.1 Normalised difference method

This method builds a relationship between the focal station and surrounding stations, then uses this relationship to predict rainfall at the focal station using Equation 2.

Equation 2

$$P_A = \frac{\sum_{t=1}^{n} \frac{NR_A}{NR_i} * P_i}{n}$$

(Di Piazza et al., 2011)

P_A is the predicted rainfall at the focal station,
NR_A (normal rainfall) is the average rainfall for that time period at the focal station,
NR_i (normal rainfall) is the average rainfall for that time period at the supporting stations,
P_i is the observed rainfall at that station,
n is the number of stations from which data is sourced.

This technique is useful when specific location data is not available or where proximal stations do not have a strong correlation but it is limited by the spatial variability of weather patterns and the lack of significant seasonality in the UK. In addition, this technique has no bias to either strong correlated relationships or proximal stations and the approach uses statistical, not causal relationships between stations to drive an estimation of the rainfall. The weakness of this approach is that there is no weighting mechanism to influence the predicted values to more representative, better correlated or more reliable stations without incorporating a further calculation.

4.6.2.1.2 IDW

The IDW method for estimating hydrological data relies on positive spatial autocorrelation (Vasiliev,

1996), in which proximal data is likely to show greater correlation than distant data (Griffith, 1987;

Dubin, 1998) a principle formulated by Tobler (1970). The IDW uses Equation 3.

Equation 3

$$Z(x) = \frac{\sum w_i z_i}{\sum w_i}$$

(Di Piazza et al., 2011)

Z is the rainfall at the focal station (x),
w_i is the distance weighting,
z_i is the rainfall at the sample station.

This function places a weighting on interpreted results assuming proximal correlation, this makes the

closest proximal gauge (Barnard Castle) the most influential station in relation to supplying data for

Brignall. A limitation of this technique is that proximal correlation may not be observed or accurate.

In this case, Brignall has lower correlation to Barnard Castle than to the rain gauge at Forcett. Other

limitations include no consideration for elevation, topography or weather patterns/movements.

4.6.2.1.3 Distance power method

This method works on the same principle as the IDW method; however, it enhances weighting to

proximal stations and is displayed in Equation 4.

Equation 4

$$P_A = \frac{\sum_{i=1}^{n} P_i/D_i^2}{\sum_{i=1}^{n} 1/D_i^2}$$

P_A is the rainfall at the focal site,
P_i is the rainfall at the sample site,
D_i is the distance between the site and sample site.

As with IDW, this function places a proximal weighting on interpreting results, making Barnard Castle

the most influential station in relation to supplying data for Brignall. A limitation of this technique is

that proximal correlation may not occur and data does suggest this is the case for Brignall. Other

limitations include no consideration for elevation, topography or weather patterns/movements.

4.6.2.1.4   Results

Before these methods were used to predict the missing period, they were employed to predict the data for the rest of 2015. The correlation was then used to better inform the choice of technique used to predict the missing data and the comparisons are shown in Table 4.1. The choice was supported by a qualitative appraisal of the results by plotting the predictions against the observed results on a graph. Using Table 4.1 it can be seen that the monthly average normal difference calculations using the three full datasets offers the best correlation between predicted and observed rainfall for the year.

Table 4.1 **Correlation table for predicted values**

Technique	Adjustments to each technique for data variations	Correlation between predicted and observed rainfall
Monthly average normal difference calculations	Predicted monthly average	0.71
	Adjustment to accommodate missing data	0.77
	Predicted using three full datasets	0.77
	Predicted without Richmond data	0.71
Annual average normal difference calculations	Predicted annual average	0.70
	Adjustment to equation to accommodate missing data	0.76
	Predicted using only three full datasets	0.77
	Predicted without Richmond data	0.70
Distance power method	Predicted using all values assuming missing values are 0	0.54
	Predicted with missing values removed	0.67
	Predicted using only three full datasets	0.54
	Predicted without Richmond data	0.54
IDW	Predicted assuming missing values are 0	0.62
	Predicted with missing values removed	0.60
	Predicted using only three full datasets	0.69
	Predicted without Richmond Data	0.59

4.6.3   Sensitivity analysis

Sensitivity analysis supports parameterisation, calibration and optimisation of hydrological models (Mishra, 2009; Song et al., 2015) and is used when characteristics cannot be comprehensively measured (Foglia et al., 2009). Sensitivity analysis can determine which factors have the greatest influence on simulated hydrological response (Tang et al., 2007). Preliminary assessment assists with

calibration by identifying the parameters that have the strongest influence on model outputs (Crosetto et al., 2000). As performed in previous studies using CRUM3 (Pattison, 2010; Hill, 2011; Pearson, 2016) parameters are assigned upper and lower bounds using literature and then systematically adjusted. Through appraisal of outputs a parameter–response relationship can be developed. The greater the response the more significant a parameter may be, although relationships may be non-linear and there may be unanticipated interactions between parameters.

4.6.4   GLUE

Parameter selection within complex multi-parameter distributed models has led to concepts of equifinality (Beven, 1993, 2001, 2011; Beven & Freer, 2001), whereby different combinations of input parameters can produce a similar 'correct' output and, in doing so, misrepresent catchment processes (Pechlivanidis et al., 2011). The GLUE approach developed by Beven and Binley (1992) uses Bayesian estimators to appraise whether or not the different combinations of model parameters are good predictors of catchment hydrological behaviour (Wainwright & Mulligan, 2004). The GLUE approach uses a Monte Carlo simulation and likelihood measures to weight the behavioural models based on an objective function, rejecting the non-behavioural ones (Pechlivanidis et al., 2011; Smith, 2012). The threshold of this weighting mechanism is the primary limitation of this approach (Pechlivanidis et al., 2011). The results of GLUE analysis capture the predictive uncertainty of the model.

4.6.4.1   Objective function choices

The GLUE approach produces a range of model runs, each with different parameter combinations and which could perform equally well when predicting observed flow (Pechlivanidis et al., 2011). The results were appraised against performance indicators, and a combination of Nash–Sutcliffe efficiency (NSE) (Equation 5), log Nash–Sutcliffe efficiency (LNSE) (Equation 6) and absolute flood peak ratio (AFPR) (Equation 7) was determined as the most suitable for selecting the particular parameter combinations to be used for simulations. From the GLUE results, an ensemble set of 25

parameter sets was selected to be used in simulation modelling, the 10 with the highest NSE, the 10

with the highest AFPR and the 10 highest results of AFPR multiplied by NSE (5 had already been

selected in the other two classifications). These runs then contributed to the calculation of the

predictive uncertainty within the overall model results displayed in chapters 5, 6, 7 and 8. Nash–

Sutcliffe efficiency is displayed in Equation 5.

Equation 5

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

O_i is the observed discharge at a given time i,
P_i is the observed discharge at a given time i,
$\bar{O}$ is the average observed discharge.

The log Nash–Sutcliffe efficiency is displayed in Equation 6.

Equation 6

$$LNSE = 1 - \frac{\sum_{i=1}^{n} ln(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

O_i is observed discharge at a given time i,
P_i is observed discharge at a given time i,
$\bar{O}$ is average observed discharge.

NSE and LNSE have values between 1 and $-\infty$ and values approaching 1 show better correlation of

observed and simulated discharge. AFPR is calculated using Equation 7.

Equation 7

$$AFPR = 1 - \left(abs\left(1 - \frac{P_{max}}{O_{max}}\right)\right)$$

P_{max} is the maximum predicted discharge,
O_{max} is the maximum observed discharge,
abs ensures it is an absolute value.

The greatest possible AFPR value is 1, in which observed and predicted maximum discharges are

equal.

4.7   Modelling of interventions for flood risk reduction

Following the results of the sensitivity and GLUE analysis, CRUM3 can be used to simulate a variety of intervention measures, including land cover change (see Section 4.7.1), attenuation features (see Section 4.7.2) and in-channel flow restrictions (see Section 4.7.3).

4.7.1   Land cover change

Simulating land cover change within the CRUM3 model was performed by adjusting the CEH land cover map 2007 (LCM2007) (Centre for Ecology & Hydrology, 2011) within the model. As in Smith (2012) and Pearson (2016) the land cover was simplified, and nine categories were reduced to six: deciduous woodland; coniferous woodland; arable land; improved grassland; rough grassland; and urban (ALFA, 2016). The individual classes were assigned parameters using the GLUE analysis and these included vegetation height, dynamic layer depth, soil porosity and saturated conductivity.

Initially, blanket cover was simulated to provide the upper bound for land cover modification in the catchment. Other drivers were also investigated, for example, proximity to watercourses, topographic drivers and hedgerows. In addition, more complex simulation drivers were investigated using SCIMAP-Flood risk mapping, and other drivers were also considered, for example, alternative funding sources, including CSF. All simulations performed are displayed in Table 4.2.

***Table 4.2* Simulations used for land cover change**

	Blanket change	Watercourse buffers	Increasing resistivity	Miscellaneous
Variables	BLW	Single buffer, 25m, 50m, 75m, 100m, BLW, CW, RG, IG	Increasing resistivity of all	Topography-driven woodland
	CW	Double buffer, 25–50m, 50–100m BLW–CW, BLW–RG, BLW–IG, CW–RG, CW–IG, RG–IG	Arable land to: BLW, CW, RG, IG	SCIMAP-Flood 1
	RG	Triple buffer, 25–50–100m BLW–CW–RG, BLW–CW–IG, BLW–RG–IG, CW–RG–IG	Improved grassland to: BLW, CW, RG	SCIMAP-Flood 2
	IG			Hedgerow strips
	ARA			Increasing resistivity
				CSF

BLW: Broadleaf/deciduous woodland; CW: Coniferous woodland; RG: Rough grassland; IG: Improved grassland; ARA: Arable land.

4.7.2 Attenuation

Simulating attenuation within CRUM3 requires the modification of the DEM used to drive the model by building in a depression and downslope embankment. At 50m resolution, this means a minimum pond size of 2500m^2 with a berm requiring between 2500m^2 and 12500m^2 of downslope adjustment. The large cell size also means that modification of height can be up to 10m vertically to create a plateau/basin. This means the approach can only be used to illustrate the concept and cannot be developed into a detailed design. As a result, other detailed modelling approaches are required at the hillslope scale.

CRUM3 does not allow modification of channel elevation or lowering in adjacent cells (Figure 4.13), which means that attenuation linked to the watercourse or floodplain cannot be simulated.
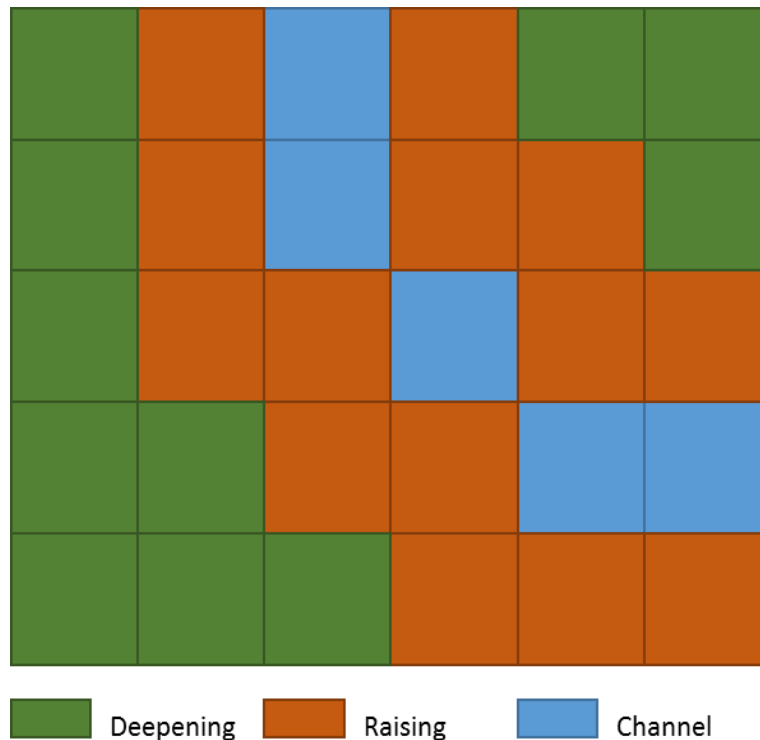
Figure 4.13 Restrictions on inserting attenuation across the catchment using the CRUM3 hydrological model.

4.7.3 Flow restrictions/LWD

It is difficult to simulate mitigation measures in the channel at the catchment scale due to the complex hydraulics surrounding flow through these features (Pearson, 2016). CRUM3 simulates such features by applying a flow restriction at an individual channel reach (Figure 7.1). It was determined by Nisbet et al. (2011) that LWD should not be inserted in channels greater than 5m wide and fieldwork shows the channel does not exceed that width. Another consideration highlighted is that drainage areas greater than 2km may require significant river and floodplain engineering.

Variations in discharge throughout the stream network mean the level of restriction needs to change accordingly to be effective in restricting flow. A limitation of CRUM3 is that the model does not allow features to overtop, meaning structures cannot be accurately represented.

4.8 Assessing effectiveness

Catchment drivers dictate the effectiveness of interventions, notably flood risk and change, as well as the conditions necessary for delivering changes. This study will not quantitatively assess costs and

benefits of individual opportunities; instead, anecdotal information and stakeholder engagement will be used.

The effectiveness of simulated interventions will be assessed using impact on peak discharge, and initial assessment will use mean peak with consideration of the uncertainty using the 10th and 90th percentile boundaries. The reason for doing this is that the main mechanism driving flood risk in Tutta Beck is peak discharge. However, there is no specific threshold to use to target a reduction due to a lack of detail with regard to the capacity of the canalised section. The additional benefit of targeting peak flow reductions is that the outputs will align with other schemes targeted at a solution in which the receptor is stored upstream.

4.9   Summary

This chapter outlines the methods used in this research, describing the processes and requirements of the CRUM3 hydrological model. The mechanisms used to create a behavioural representation, such as sensitivity analysis and the GLUE approach, are also introduced. The development of scenarios involved stakeholder engagement, SCIMAP-Flood risk mapping, a review of literature and the appraisal of funding mechanisms. The results of these simulations are presented in chapters 5, 6, 7 and 8.

Chapter 5   Assessing the Effects of Vegetation Change on Hydrology

5.1 Introduction

This chapter presents the results of land cover change simulations, scenarios are developed from a review of literature, fieldwork and stakeholder engagement. Land cover changes influence hydrology in a similar way to land management changes. Therefore, the land cover change scenarios in this chapter are a proxy for conceptualising the benefits of land management changes.

The LCM has been rationalised by grouping hydrologically similar uses to form the six classes displayed in Figure 5.1 and Table 5.1.
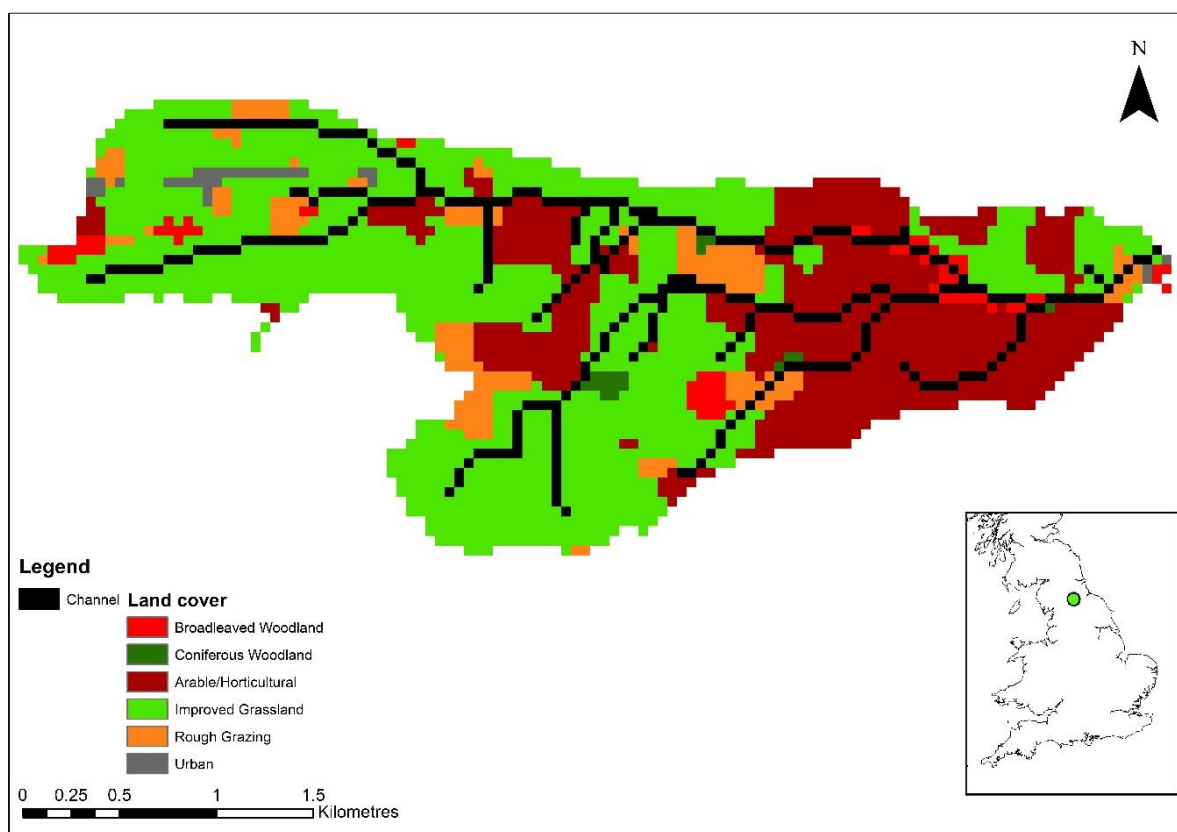
Figure 5.1 **LCM of the Tutta Beck catchment (Morton et al., 2011).**

Table 5.1 **Land cover data for the Tutta Beck catchment, the total catchment size being 706.25ha**

Land cover	Land take (ha)	Percentage cover
Deciduous woodland	25.25	3.38%
Coniferous woodland	60	0.85%
Arable and horticultural	212.25	27.79%
Improved grassland	394.5	56.72%
Rough grassland	60.25	9.65%
Developed areas	8	1.6%

Section 5.2 explains how interventions are targeted correctly and Section 5.3 details the results of blanket land cover change simulations. Section 5.4 reports the results of watercourse-driven land cover change simulations and Section 5.5 details the results of topography-driven land cover change simulations. Section 5.6 reports the results of using SCIMAP-Flood risk mapping to target land cover change in high-risk areas and Section 5.7 details the results of bespoke land cover change simulations. Section 5.8 summarises the chapter and Section 5.9 presents recommendations.

5.2   Targeting mechanism for interventions

A key challenge for the implementation and effectiveness of NFM is siting interventions to ensure they have the greatest impact. Interventions can be installed anywhere, but if catchment processes prevent them operating as designed, they will not deliver the desired benefits. To answer research objective 1, **developing a framework for implementation,** and research objective 4, **assessing whether or not SCIMAP-Flood is suitable as a targeting mechanism for FRM interventions,** it is necessary to simulate different approaches to targeting interventions.

The differing responses of different land covers to wetting can be conceptualised as their 'resistivity' to overland flow. For a given land cover, resistivity is used to identify whether rainfall response would increase/decrease that location's resistance to the formation and propagation of overland flow.

5.3   Blanket changes

The first assessment of land cover is a blanket change to ascertain the maximum potential for land cover change across the catchment. Table 5.1 shows the existing land use, including the percentage change required to cover the catchment with each different land use, and Figure 5.2 shows the results of blanket change simulations.

Table 5.2 **Land cover characteristics for blanket change assessments**

Land cover	Percentage change
Deciduous woodland	<u>279.7%</u>
Coniferous woodland	<u>11770%</u>
Arable and horticultural	<u>332.7%</u>
Improved grassland	<u>179%</u>
Rough grassland	<u>1172.2%</u>
Urban	<u>8828%</u>
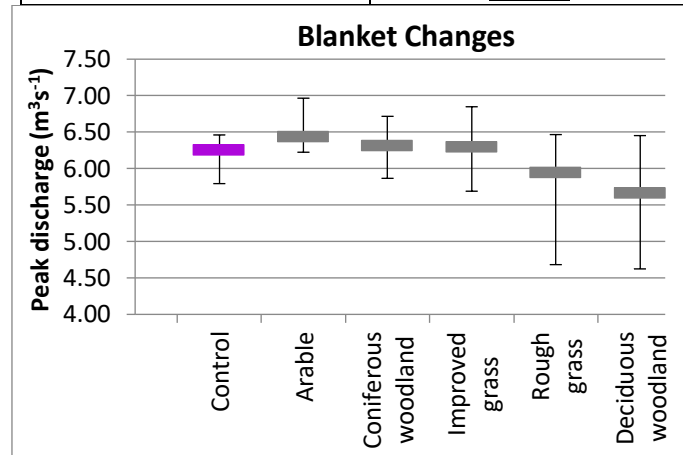
Figure 5.2 **Graph showing blanket land cover changes for the Tutta Beck catchment. The X axis shows the change in land cover, the Y axis the peak discharge from the simulations and the error bars the 90th and 10th percentile for the individual model runs performed for each simulation.**

The blanket change simulation shows the greatest possible impact on peak flows from land cover change. Figure 5.2 shows the results of catchment-wide application of different land covers. Deciduous woodland would reduce simulated mean peak discharge to $5.67m^3s^{-1}$, a $0.58m^3s^{-1}$ reduction (9.25%), whereas rough grassland would reduce simulated mean peak discharge to $5.95m^3s^{-1}$, a $0.31m^3s^{-1}$ reduction (4.91%). The blanket application of arable land, coniferous woodland and improved grazing would all result in increased mean peak flow. As the reduction through deciduous woodland is less than 10% it is anticipated that any land cover change intervention would require the application of another complementary technique.

5.4 Watercourse-driven land use change

Watercourses offer the most efficient way of transporting water and in cases in which runoff can connect directly to watercourses there is an increased likelihood of rapid contributions to peak flow. This section will investigate whether or not land use change targeted at watercourses can reduce

peak flows downstream. This will be done in the form of a buffer around the channels within the

CRUM3 input dataset.

5.4.1 Scenario development

There are several ways in which watercourses can be targeted, including the variation of the width

and form of a buffer strip. The methods to be investigated are displayed in Table 5.3 and Figure 5.3.

Table 5.3 **Watercourse-driven land use change**

Method to be appraised	Key assessment	Land changes to be assessed
Buffer width change	25m 50m 75m 100m	Deciduous woodland Coniferous woodland Rough grassland Improved grassland
Two buffers	25m–50m 50m–100m	Deciduous woodland Coniferous woodland Rough grassland Improved grassland
Three buffers	25m–50m–75m	Deciduous woodland Coniferous woodland Rough grassland Improved grassland
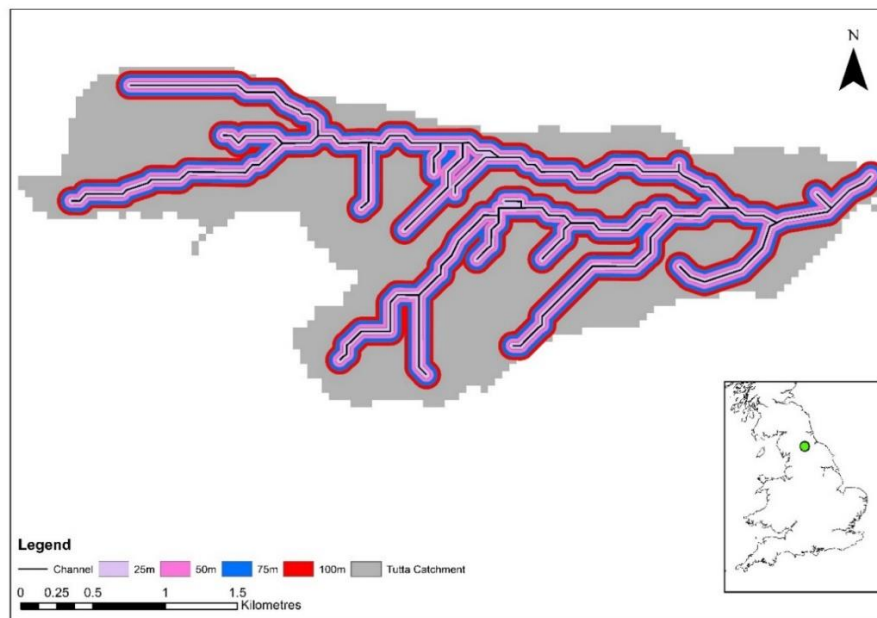
Figure 5.3 **The four different buffer widths used in simulations.**

5.4.2 Single buffer results

Inserting a single buffer strip would be the simplest way of disconnecting watercourses from

adjacent hillslopes. The simulations are displayed in Figure 5.4 and the results in Table 5.4.
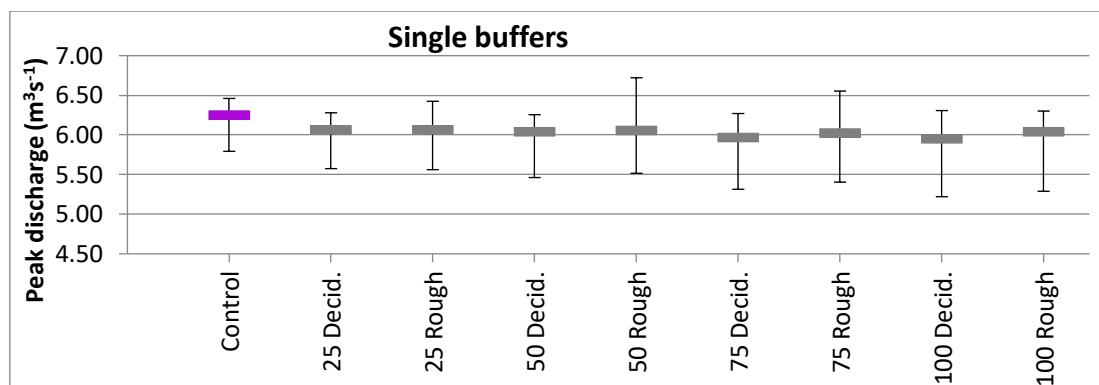
Figure 5.4 Graph showing results of buffer simulations across the catchment.

Table 5.4 **Land take of each simulation**

Buffer width	25m	50m	75m	100m
Land take	86.5ha	145.25ha	219.75ha	288.5ha
Percentage of catchment	12.25%	20.57%	31.12%	40.85%
Deciduous mean peak discharge	$6.06m^3s^{-1}$	$6.05m^3s^{-1}$	$5.97m^3s^{-1}$	$5.95m^3s^{-1}$
Rough grassland mean peak discharge	$6.07m^3s^{-1}$	$6.06m^3s^{-1}$	$6.03m^3s^{-1}$	$6.04m^3s^{-1}$

The results show the largest reduction was through the 100m deciduous woodland buffer reducing simulated mean peak discharge to $5.95m^3s^{-1}$, a $0.30m^3s^{-1}$ reduction. The larger buffer reduces discharge to $0.11m^3s^{-1}$, which is more than the 25m buffer; however, it requires 202ha more land. It may be more efficient to use the 25m buffer for flood mitigation alongside a complementary technique.

5.4.3 Two buffer results

Inserting two buffers around a watercourse provides different opportunities for land managers. For example, if both a deciduous woodland and a rough grassland buffer were to be inserted, the deciduous woodland could provide the benefits of disconnecting the hillslope runoff while the rough grassland would provide a less intensively exploited crop. The simulations are displayed in Table 5.5 and the results in Figure 5.5.

Table 5.5 **Land cover change simulations with two buffers**

	0–25m and 25–50m buffer simulation [results displayed in Figure 5.5(a)]					
	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5	Simulation 6
0–25m land cover	Deciduous woodland	Deciduous woodland	Deciduous woodland	Coniferous woodland	Coniferous woodland	Rough grassland
25–50m land cover	Coniferous woodland	Rough grassland	Improved grassland	Rough grassland	Improved grassland	Improved grassland
Simulated mean peak discharge	$6.06m^3s^{-1}$	$6.07m^3s^{-1}$	$6.08m^3s^{-1}$	$6.07m^3s^{-1}$	$6.08m^3s^{-1}$	$6.08m^3s^{-1}$
	0–50m and 50–100m buffer simulation [results displayed in Figure 5.5(b)]					
	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5	Simulation 6
0–50m land cover	Deciduous woodland	Deciduous woodland	Deciduous woodland	Coniferous woodland	Coniferous woodland	Rough grassland
50–100m land cover	Coniferous woodland	Rough grassland	Improved grassland	Rough grassland	Improved grassland	Improved grassland
Simulated mean peak discharge	$6.07m^3s^{-1}$	$6.00m^3s^{-1}$	$6.07m^3s^{-1}$	$6.07m^3s^{-1}$	$6.13m^3s^{-1}$	$6.12m^3s^{-1}$

(a)

(b)
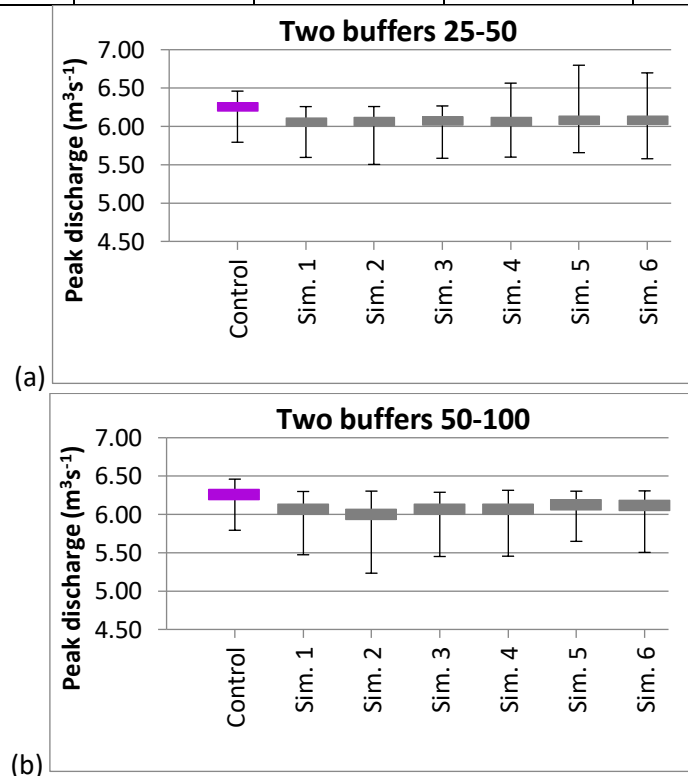
Figure 5.5(a) **Graph showing results of inserting variable land covers with 0–25m and 25–50m buffers;** *(b)* **Graph showing results of inserting variable land covers with 0–50m and 50–100m buffers.**

In Figure 5.5(a) the greatest reduction was through the insertion of deciduous and coniferous

woodland. This reduced peak flows to $6.06m^3s^{-1}$, a $0.19m^3s^{-1}$ reduction. In Figure 5.5(b) the greatest

simulated mean peak discharge reduction was through the insertion of deciduous woodland and

rough grassland land covers. This reduced peak flows to $6.0m^3s^{-1}$.

All results show a reduction in simulated discharge; however, the difference between the results of the two different buffer width simulations is insignificant. Only the deciduous woodland and rough grassland scenario is greater than ±0.01m^{3}s^{-1}, with a 0.07m^{3}s^{-1} larger reduction. Due to the insignificant difference between the results and the difficulty in establishing a 100m buffer around watercourses the smaller two buffer scenario would be more suitable.

5.4.4 Three buffer results

A three-buffer simulation was also be carried out to maximise the chances of the final buffer chosen being an agriculturally functional land cover such as rough grassland or improved grazing. The simulations are displayed in Figure 5.6 and the results in Table 5.6.

Table 5.6 **Land cover change simulations with three buffers**

	Simulation 1	Simulation 2	Simulation 3	Simulation 4
0–25m land cover	Deciduous woodland	Deciduous woodland	Deciduous woodland	Coniferous woodland
25–50m land cover	Coniferous woodland	Coniferous woodland	Rough grassland	Rough grassland
50–100m land cover	Rough grassland	Improved grassland	Improved grassland	Improved grassland
Results	6.04m^{3}s^{-1}	6.08m^{3}s^{-1}	6.06m^{3}s^{-1}	6.07m^{3}s^{-1}
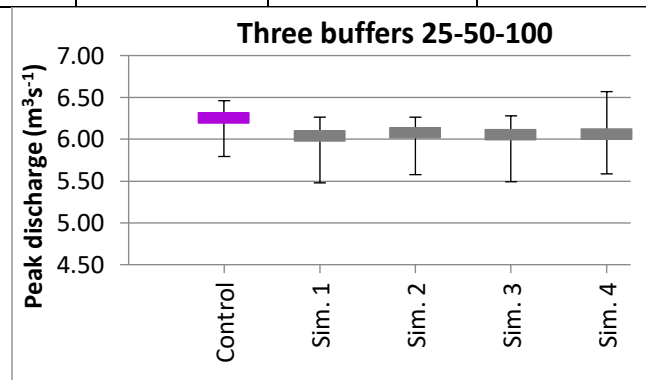
Figure 5.6 **Graph showing results of the three buffer simulations.**

The greatest reduction was Simulation 1, which reduced peak discharge to 6.04m^{3}s^{-1}, a 0.21m^{3}s^{-1} reduction. The variation between results was small with a range of 0.04m^{3}s^{-1}. The largest reduction was achieved by using a deciduous woodland internal buffer (0–25m), coniferous woodland medial buffer (25–50m) and rough grassland external buffer (50–100m). The smallest reduction appeared when using a deciduous woodland internal buffer (0–25m), a coniferous woodland medial buffer

(25–50m) and an improved grassland external buffer (50–100m), which produced a simulated mean peak discharge of 6.08m^{3}s^{-1}.

5.5   Topography-driven land use change

Elevated gradients increase the likelihood of runoff being generated. This section targets areas of the catchment with high gradients and targets land cover change at these locations. Figure 5.7 shows the gradients across the catchment. The light blue intervention areas are used to disconnect the slope-generated runoff from entering the watercourses.
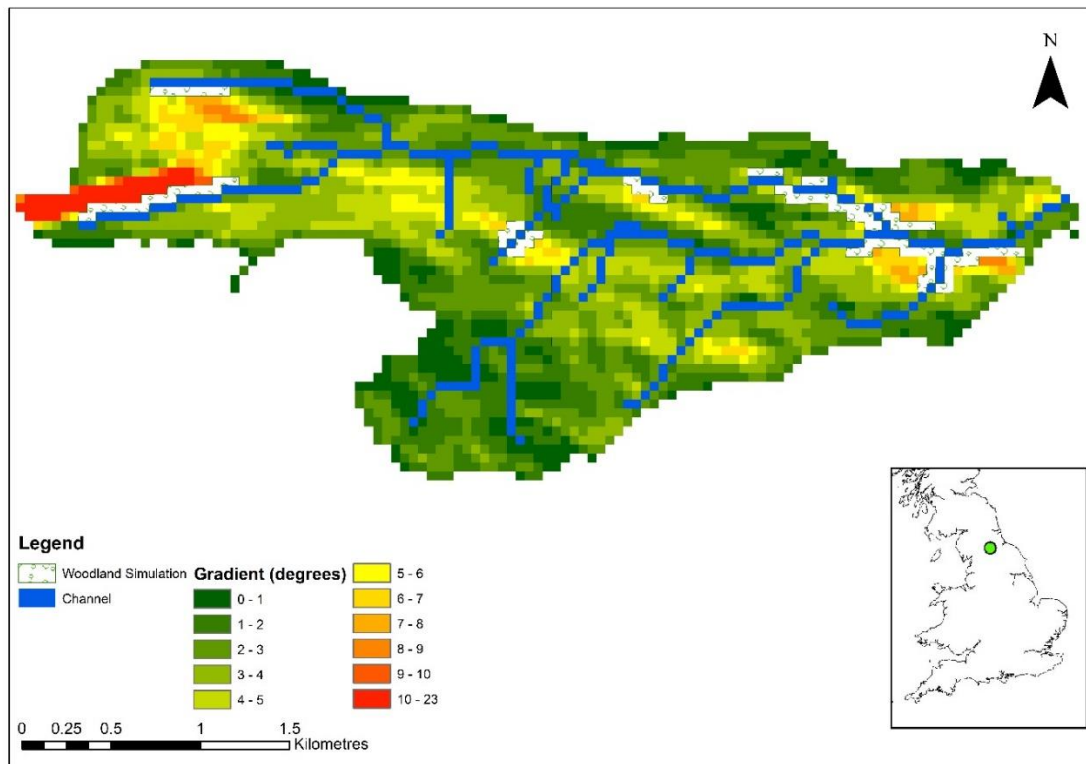
Figure 5.7 Map of gradients throughout the Tutta Beck catchment and location simulations.
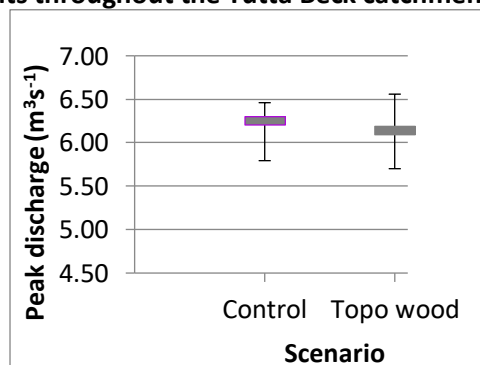
Figure 5.8 **Graph showing results of a topography-driven woodland insertion.**

The insertion of topography-driven woodland reduces simulated mean peak discharge to 6.14m^{3}s^{-1}, a 0.11m^{3}s^{-1} reduction. However, in reviewing the LCM, a large portion of the area in this simulation is already classed as deciduous woodland land cover. This simulation suggests that to see measurable benefits, larger areas of the catchment need to be changed and that targeting application to small areas driven solely by topography is not effective.

Another option for topographic targeting in other catchments is to change the land cover across high-risk slopes. This is not feasible in this catchment due to the pressure on farmable area; however, in a larger catchment with more upland area this could provide an opportunity.

5.6   SCIMAP-Flood-driven land use change

SCIMAP-Flood uses multiple inputs to generate a risk rating and can, therefore, be used to target interventions at the highest cumulative risk of rapid connectivity. This section investigates the use of SCMAP-Flood as a suitable mechanism for targeting flood mitigation interventions.
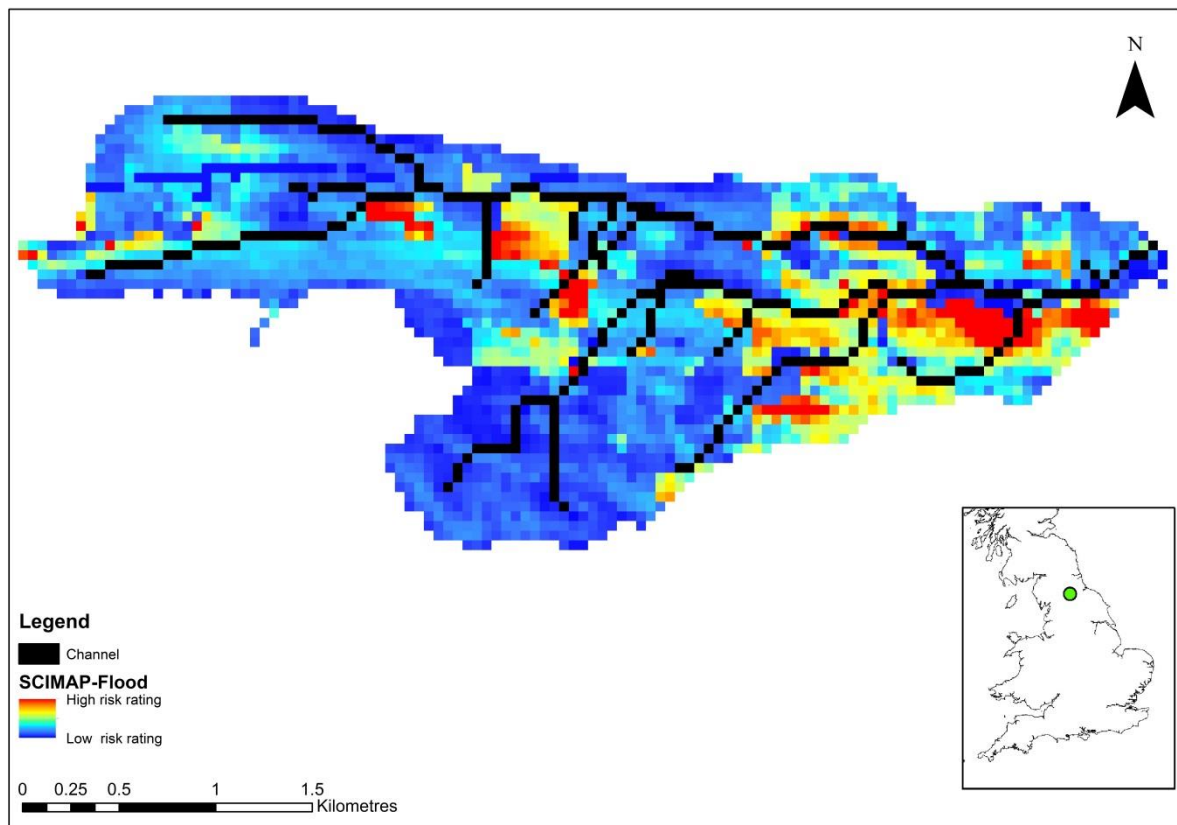
Figure 5.9 **SCIMAP-Flood risk map for the Tutta Beck catchment. The warmer colours denote the highest risk of runoff contribution to flood risk.**

5.6.1   Scenario development

Using Figure 5.9 there are several potential scenarios for targeting land cover change. These scenarios were appraised and the following two offered the greatest potential effectiveness:

1. targeting the downslope area with the aim of reducing the connectivity of a high-risk area to the central watercourse, as shown in Figure 5.10;

2. replacing the land cover across the high-risk areas, as shown in Figure 5.11.
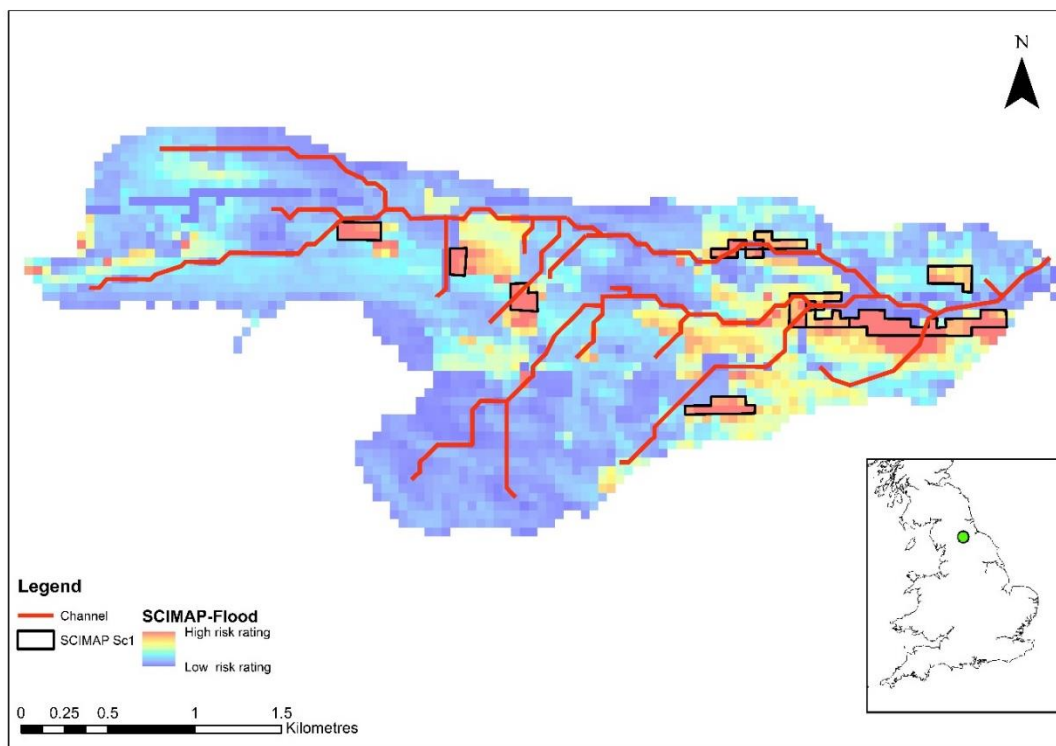
Figure 5.10 **Scenario 1 overlaid on the SCIMAP-Flood risk map of the Tutta Beck catchment.**
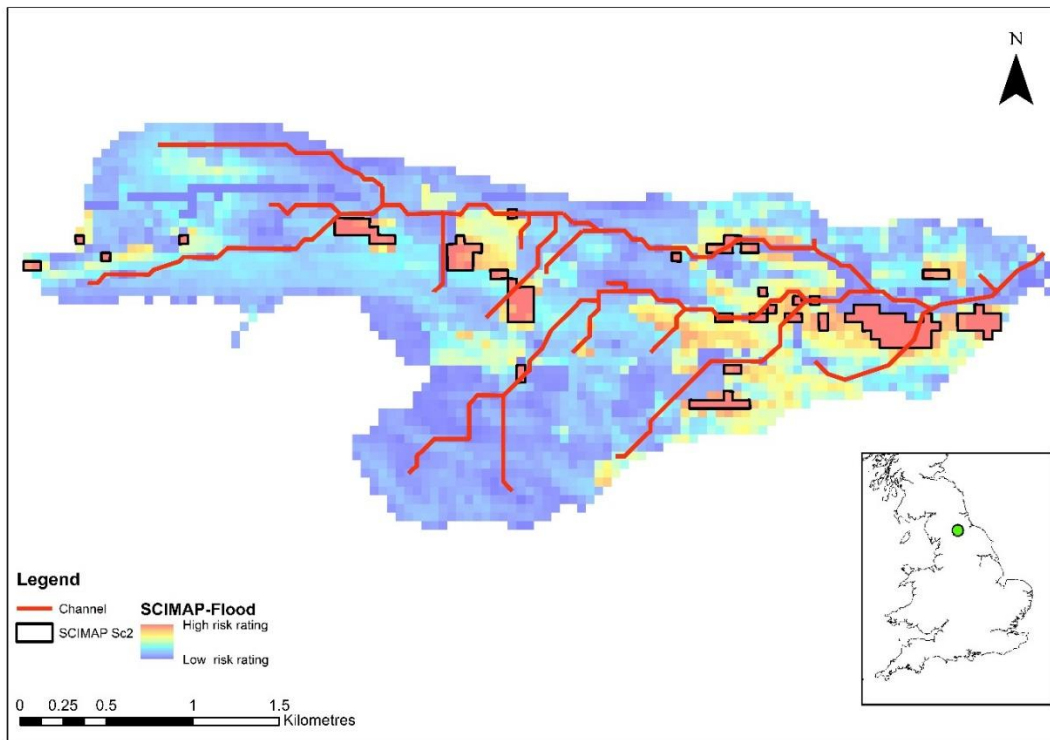
Figure 5.11 **Scenario 2 overlaid on the SCIMAP-Flood risk map of the Tutta Beck catchment.**

5.6.2   Scenario 1 results

Using the land cover change scenario shown in Figure 5.10, simulations were run using the four most

resistive land covers, the results of which are shown in Figure 5.12.
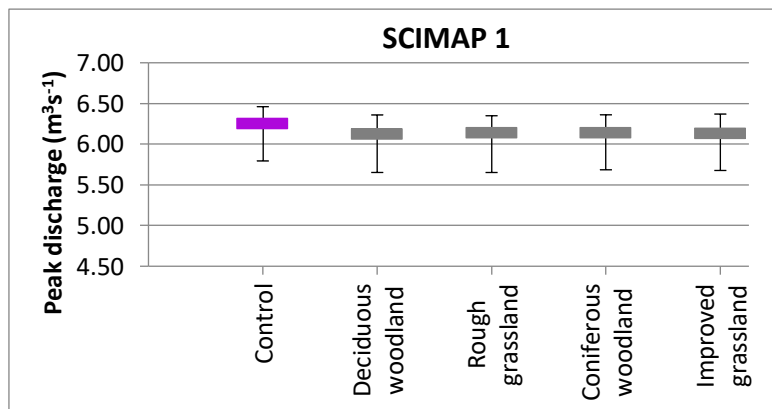
Figure 5.12 **Graph showing results of simulations targeted at intercepting surface water runoff from high-risk areas throughout the Tutta Beck catchment.**

These simulations all yielded minimal reductions in peak flow. The greatest reduction was through

the application of deciduous woodland, which reduced peak flows to $6.13 m^3 s^{-1}$, a $0.12 m^3 s^{-1}$

reduction. The results of all simulations were within $0.02 m^3 s^{-1}$ of this discharge rate. As can be seen

from the results, targeting land cover change to intercept areas of elevated risk as identified from

SCIMAP-Flood does not yield a large enough reduction in peak flow to justify investigation as a sole mitigation strategy.

5.6.3   Scenario 2 results

Using the land cover change scenario shown in Figure 5.11, simulations were run using the four most resistive land covers, the results of which are shown in Figure 5.13.
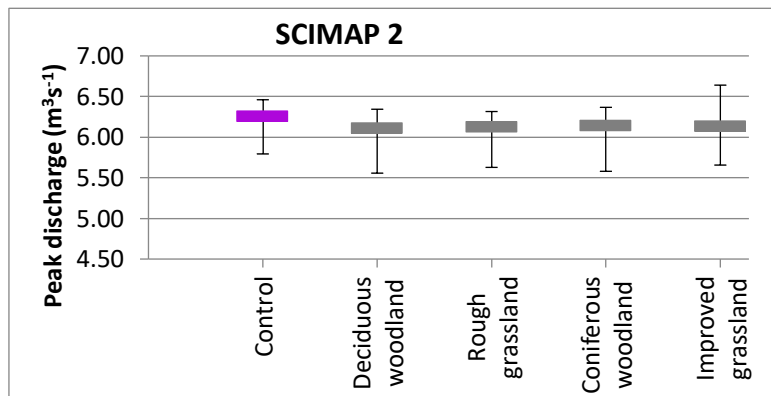
Figure 5.13 **Graph showing results of simulations covering high-risk areas in the Tutta Beck catchment.**

These simulations all yielded minimal reductions in peak flow. The greatest reduction was through the application of deciduous woodland, which reduced peak flows to $6.12m^3s^{-1}$, a $0.13m^3s^{-1}$ reduction. The results of all simulations were within $0.02m^3s^{-1}$ of this discharge rate. As can be seen from the results, targeting land cover change at the very highest risk areas identified using SCIMAP-Flood does not yield a large enough reduction in peak flow to justify investigation as a sole mitigation strategy.

5.6.4   Summary

In reviewing the results of the simulations displayed in sections 5.6.2 and 5.6.3 it is likely that the ambition of targeting minimal interception or only the highest risk area, involved the change of too little of the catchment to offer a large enough reduction in simulated mean peak discharge for this approach to be suitable for flood mitigation. It may be possible to utilise change over a larger area to deliver effective reductions; however, this would not be feasible in the Tutta Beck catchment. In other studies, the catchment area has been significantly larger with greater topographic variation

and a larger number of fields and in these locations, change has been targeted at field groups to mitigate runoff. The size and limited variation of the Tutta Beck catchment mean such an approach would not be suitable. However, comparing Figure 5.1 and Figure 5.9, the highest risk areas on the SCIMAP-Flood risk map are associated with arable land cover and the lower topographic variation in Tutta Beck makes topography less influential.

5.7 Bespoke land use change

The simulations in this section have been developed using literature, stakeholder engagement and field observations as being uniquely applicable to the Tutta Beck catchment. They may not be transferable to other catchments but are opportunities for this area.

5.7.1 Hedgerow buffer strips

The simulations in this section investigate the potential impact of expanding the hedgerows to create a barrier to overland flow propagation. Due to the relatively small field sizes and resolution shown in Figure 5.14, targeting all field boundaries was not suitable. Instead, therefore, this simulation targeted larger cross-slope boundaries to create buffer strips. Where possible, these simulations are near an existing field boundary. Communication with stakeholders indicated this simulation may be feasible to implement using a combination of Countryside Stewardship agreements and other funding streams. This section uses the risk map from SCIMAP-Flood to target the hedgerow/buffer strip simulations.
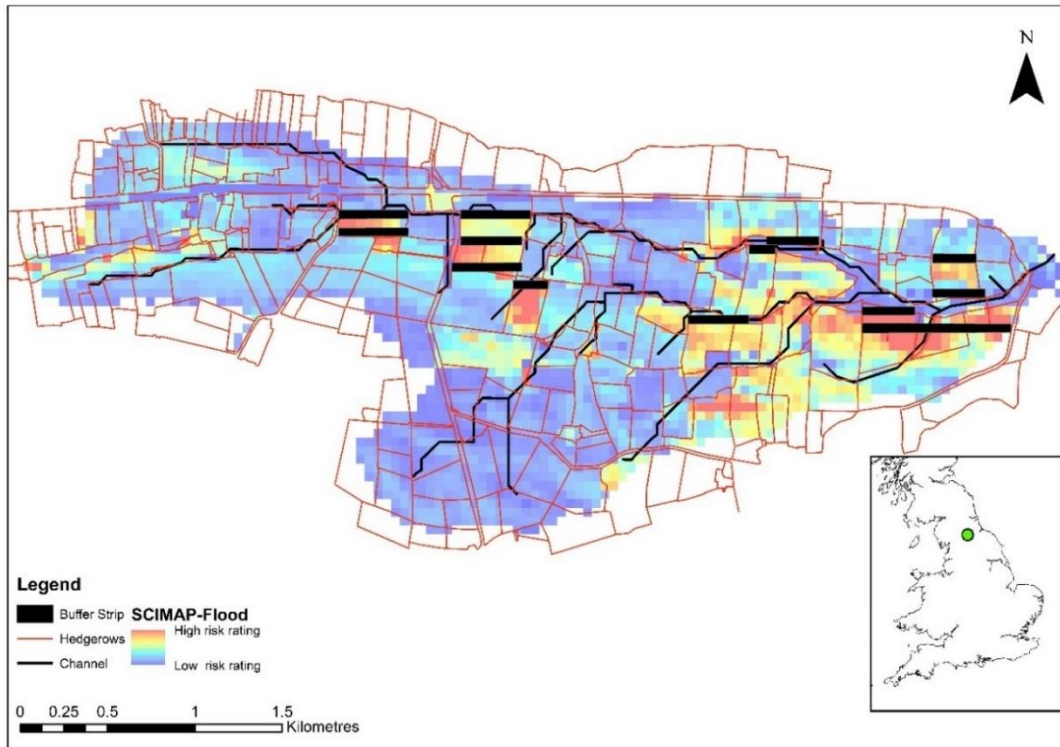
Figure 5.14 **Digitised hedgerows and SCIMAP-Flood map for the Tutta Beck catchment.**

5.7.1.1   Results

Using Figure 5.14, the buffer strip scenario was developed to intercept runoff using the four most

resistive land covers. The results of this simulation are displayed in Figure 5.15.
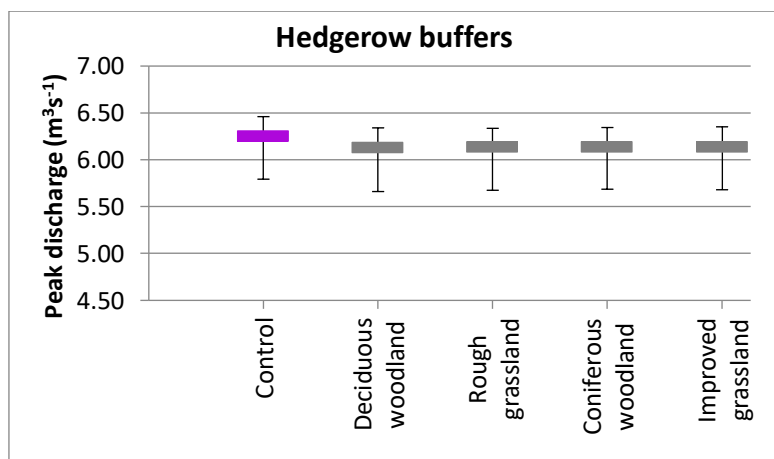
Figure 5.15 **Graph showing results of targeting hedgerow boundaries.**

These simulations all yielded minimal reductions in peak flow. The greatest reduction was through

the application of deciduous woodland, which reduced simulated mean peak discharge to $6.13 m^3 s^{-1}$,

a $0.12 m^3 s^{-1}$ reduction. All other land covers resulted in a simulated mean peak discharge of $6.14 m^3 s^{-1}$

. As can be seen from the results, targeting land cover change at thin buffer strips in the highest risk

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areas does not yield significant reductions in peak flow. In reviewing the results of other specific targeted simulations, such as those in Section 5.6, it is likely that the ambition of targeting small areas for land use change used too little of the catchment and was, therefore, unable to provide a large enough reduction in simulated mean peak discharge to justify its use as a sole strategy in a FAS. However, the minimal land take and multiple benefits may mean these techniques are worth investigating further within an agri-environment scheme should funding become available.

5.7.2   Increasing the resistivity of land covers

Across the catchment, several land covers are susceptible to the formation of runoff and the next group of simulations are targeted at improving the resistivity of these land covers. There are three simulation groups: (1) increasing the resistivity of all land covers; (2) targeting land cover change at the arable areas associated with the highest runoff risk; (3) targeting land cover change at improved grassland areas. These changes are displayed in Table 5.7.

Table 5.7 Simulations targeted at improving the resistivity of land covers across the Tutta Beck catchment

Original catchment land cover values		Simulated changes to original land cover values							
		Increase resistivity of all	Change arable land cover to…				Change improved grassland to…		
			Deciduous woodland	Coniferous woodland	Rough grassland	Improved grassland	Deciduous woodland	Coniferous woodland	Rough grassland
Deciduous woodland	1	1	1	1	1	1	1	1	1
Coniferous woodland	2	4	2	2	2	2	2	2	2
Arable/ horticultural	3	2	1	2	5	3	3	3	3
Improved grassland	4	5	4	4	4	4	1	2	5
Rough grassland	5	1	5	5	5	5	5	5	5
Urban*	6	6	6	6	6	6	6	6	6

*Introducing urban land cover would not be feasible. In addition, the development of open countryside would not be permitted.

5.7.2.1 Increasing the resistivity of all land covers

This simulation involves adjusting all land covers to increase their resistivity by the equivalent of one more resistive land cover.
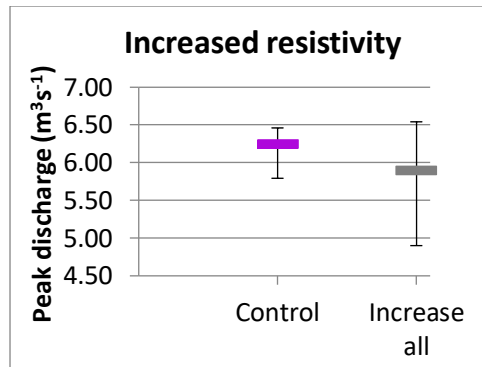
Figure 5.16 Graph showing results of increasing the resistivity of all existing catchment land cover classifications by a single land cover type.

This simulation results in a reduction in simulated mean peak discharge to $5.90m^3s^{-1}$, a $0.35m^3s^{-1}$ reduction (0.56%). The uncertainty of this result is also high at $1.64m^3s^{-1}$, which means confidence in this result is limited.

Changing all land covers would be very difficult to implement and is not feasible as part of a flood mitigation scheme. However, as mentioned previously, changing of land cover could be a proxy for land management change to improve rainfall–runoff response. For example, the simulated change of improved grassland to rough grassland could represent treatments to improve infiltration rate (soil aeration) and increased surface roughness (longer period between grazing). The simulated change of arable land to improved grassland could represent an overwinter cover crop to mimic improved grassland and improve infiltration (soil aeration). There is the potential for this approach to receive partnership funding from an agri-environment scheme.

5.7.2.2 Targeting changes at arable land

Rather than targeting changes at the whole of the catchment, it would be more practical to target the highest risk land cover. The results in this section show the impact of targeting land cover change at areas that are currently arable land.
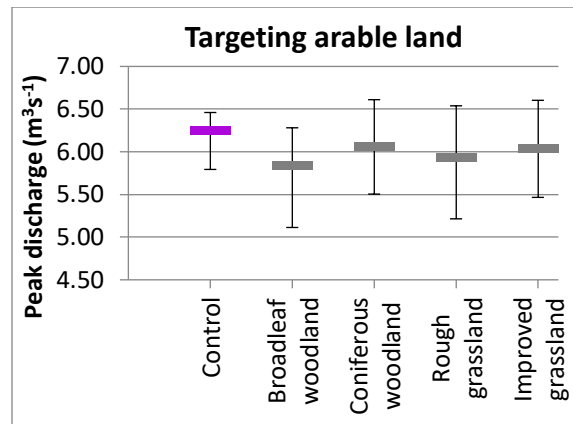
Figure 5.17 **Graph showing results of land use change targeted at existing arable land.**

The greatest reduction in discharge is through the application of deciduous woodland, which reduces the simulated mean peak discharge to 5.84m^3s^{-1}, a 0.41m^3s^{-1} (6.56%) reduction. All the simulations offer a reduction in simulated mean peak discharge, the lowest reduction being through the application of coniferous woodland and improved grassland, which reduces the simulated peak mean discharge to 6.06m^3s^{-1} and 6.05m^3s^{-1}, respectively. Simulating a change from arable land to rough grassland reduced mean peak flow to 5.93m^3s^{-1}, a 0.32m^3s^{-1} (5.12%) reduction. Although all these changes are, theoretically, feasible, they would not maintain the same level of agricultural productivity. Therefore, the opportunity to use land cover change as a proxy for land management interventions may be more suitable. This simulation targets the highest risk land cover. However, these areas are identified as having the highest risk using SCIMAP-Flood, which means that comparisons may be drawn with this intervention.

5.7.2.3   Targeting changes at improved grassland

Improved grassland is the largest area of land cover in the catchment. Therefore, by targeting land cover change simulations at this area, the potential for delivering flood mitigation benefits exists.
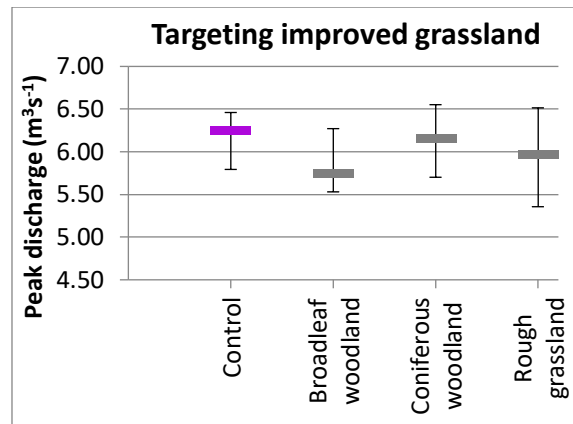
Figure 5.18 **Graph showing results of land use change targeted at existing improved grassland.**

The greatest reduction is through the application of deciduous woodland, which reduces the simulated mean peak discharge to $5.75 m^3 s^{-1}$, a $0.5 m^3 s^{-1}$ (8%) reduction. All the simulations offer a reduction in simulated peak mean discharge, the lowest reductions being through the application of coniferous woodland, which reduces simulated peak mean discharge to $6.16 m^3 s^{-1}$. Simulating a change to rough grassland reduced mean peak flow to $5.97 m^3 s^{-1}$, a $0.28 m^3 s^{-1}$ (4.48%) reduction. Although all these changes are, theoretically, feasible, they would not maintain the same level of agricultural productivity. Therefore, the opportunity to use land cover change as a proxy for land management interventions may be more suitable; techniques such as soil aeration, reducing stock densities, and timing stock and vehicle traffic could be used.

5.7.3 Targeting using CSF

The insertion of woodland has been demonstrated to be a benefit with regard to flood risk. It can also improve elements of agricultural function and increase resilience to rainfall and overland flow. As part of the literature review, a register of land designations throughout the UK called MAGIC Map was consulted. Figure 5.19 shows the locations identified within the CSF initiative as high spatial priority for planting woodland as a measure for reducing flood risk. This means that land owners/farmers could apply for support to plant woodland in these locations.
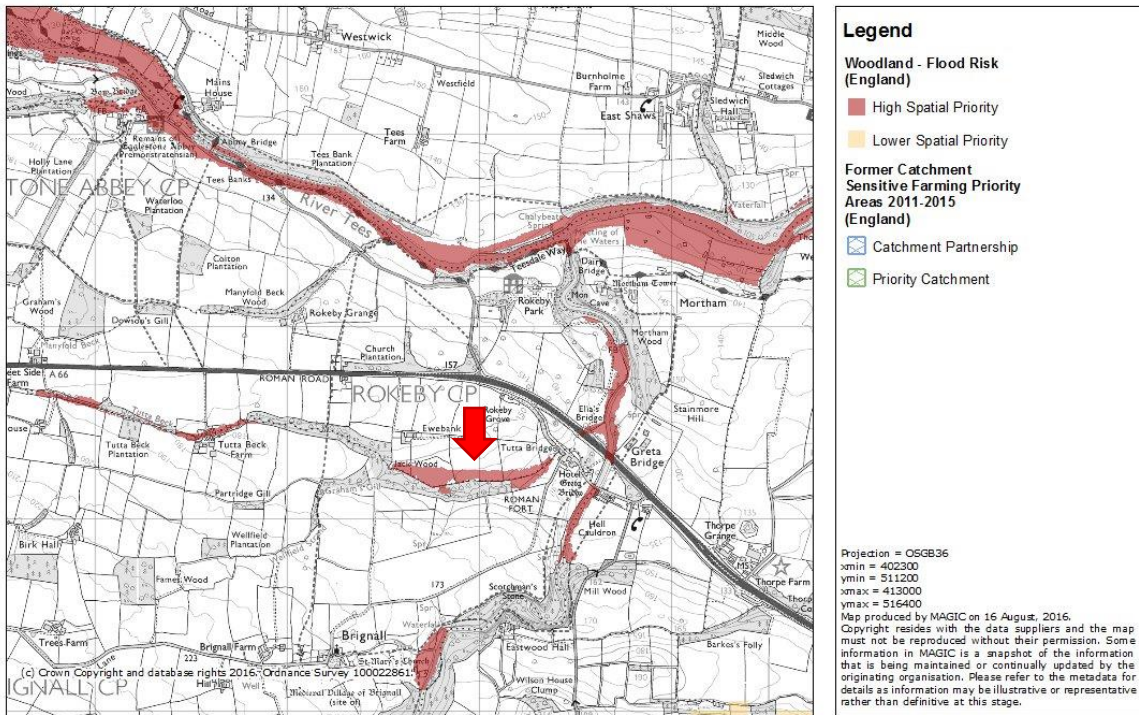
Figure 5.19 **Map showing areas targeted as being suitable for planting with woodland as a measure for reducing flood risk (England) (MAGIC Map, 2016).**

There is a significant area in the north-east of the catchment as well two smaller areas further west

that can be identified as high spatial priority for woodland planting to reduce flood risk. This land

take was then simulated within the CRUM3 hydrological model, the results of which are shown in

Figure 5.20.
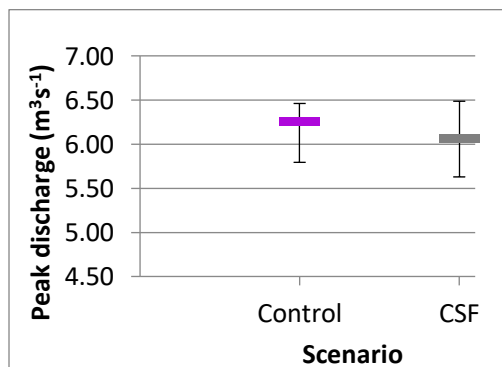
Figure 5.20 **Graph showing results of targeting woodland planting under the CSF initiative.**

This simulation reduced simulated mean peak discharge to 6.07m^3s^{-1}, a 0.18m^3s^{-1} (2.88%) reduction.

It shows that spatial targeting of woodland can provide flood mitigation benefits and that for a small

land take measurable reductions can be delivered. Field visits during Storm Desmond (5 December 2016) shown in Figure 5.21 show that under extreme conditions runoff did form in this area and that justification for woodland planting appeared well founded.

Figure 5.21 Image showing the overland flow route from the north-east of the catchment identified as a priority for targeting woodland planting for flood mitigation under the CSF initiative (author, 5 December 2016).

5.8   Summary

This chapter reviewed the suitability of using land cover change for flood mitigation across the Tutta Beck catchment and the effectiveness of the various targeting mechanisms. Through the investigation of blanket change in Section 5.2 the maximum potential for peak flow reduction was established by simulating the entire catchment as being covered by deciduous woodland. This blanket woodland scenario would not be sufficient to provide sole mitigation of flood risk throughout the catchment and means that other techniques would be required as well.

The results of the largest peak flow reductions from each targeting mechanism are displayed in Figure 5.22. This shows the second greatest reduction after blanket change was improved grassland to deciduous woodland, which reduced simulated mean peak discharge to $5.75m^3s^{-1}$, a $0.5m^3s^{-1}$ (8%)

reduction. This simulation requires the largest land take of all scenarios, but changing to deciduous would not be feasible; however, improving land management and introducing small land cover changes could deliver similar results that would be more acceptable. A similar strategy could be to target land cover change simulations at arable land. The most significant reduction here was through the application of deciduous woodland, which reduced simulated mean peak discharge to $5.84\text{m}^3\text{s}^{-1}$, a $0.41\text{m}^3\text{s}^{-1}$ (6.56%) reduction. The 100m watercourse buffer simulation offered the next lowest flow restriction at $5.95\text{m}^3\text{s}^{-1}$, a reduction of $0.3\text{m}^3\text{s}^{-1}$ (4.8%). The 75m buffer simulation offered a similar reduction to 100m at $5.97\text{m}^3\text{s}^{-1}$. The narrower 25m and 50m simulations offered lower reductions in peak flow at $6.06\text{m}^3\text{s}^{-1}$ and $6.05\text{m}^3\text{s}^{-1}$, respectively. The CSF simulation offered a reduction in simulated mean peak discharge of $6.07\text{m}^3\text{s}^{-1}$, a $0.18\text{m}^3\text{s}^{-1}$ (2.88%) reduction. Although this simulation would probably not form an integral part of a flood alleviation scheme it could provide benefits for exceedance events.
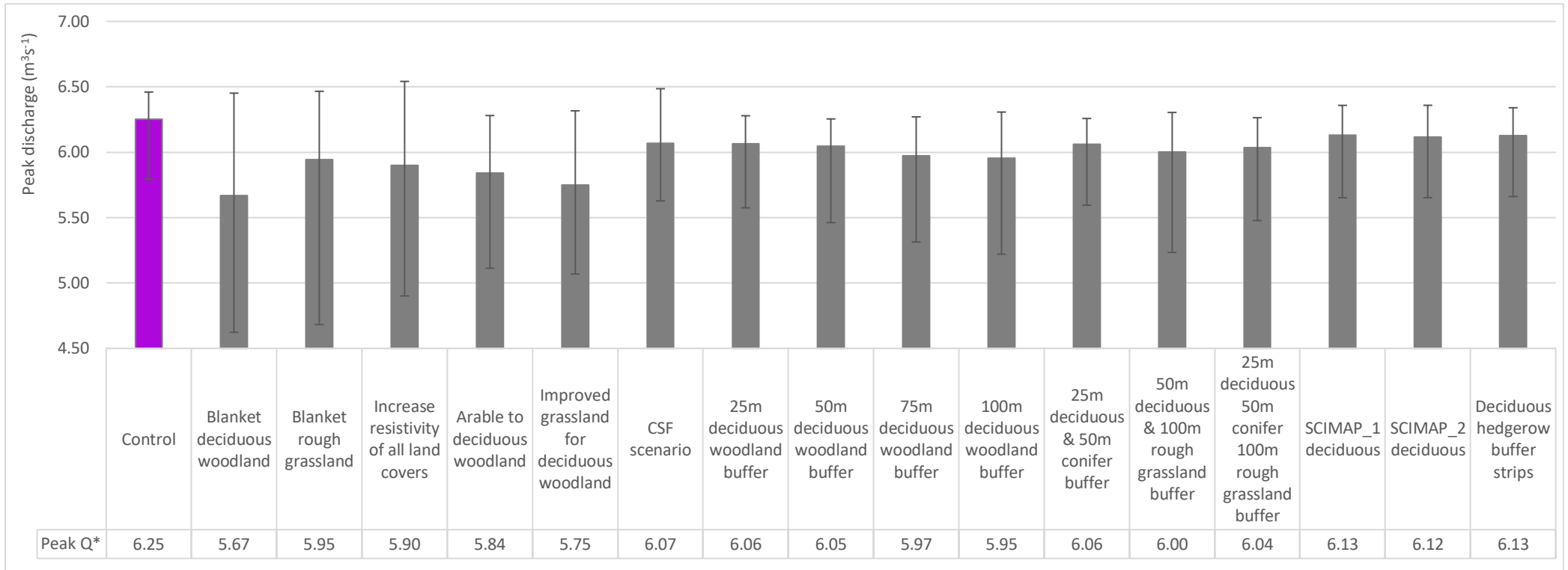
Figure 5.22 **Graph showing results of all simulations that resulted in a measurable reduction in peak discharge (*Q measured in m³s⁻¹).**

Table 5.8 **Efficiency of discharge adjustments per hectare of land take**

	Blanket deciduous woodland	Blanket rough grassland	Increasing resistivity of all land covers	Arable to deciduous	Improved grassland to deciduous	CSF scenario	25m deciduous buffer	50m deciduous buffer	75m deciduous buffer	100m deciduous buffer	25m deciduous and 50m coniferous buffer	50m deciduous and 100m rough buffer	25m deciduous, 50m coniferous and 100m rough buffer	SCIMAP_1 deciduous	SCIMAP_2 deciduous	Deciduous hedgerow buffer strips
Effectiveness m³s⁻¹ha⁻¹	0.0008	0.0004	0.0005	0.0019	0.0013	0.0058	0.0022	0.0014	0.0013	0.0010	0.0013	0.0009	0.0007	0.0042	0.0044	0.0054

One aspect that needs to be considered in relation to all simulations with regard to land take and discharge is their efficiency. The most effective reductions in simulated mean peak flow are those that offer the largest reduction in discharge for the smallest land take. To appraise this, the reductions displayed in Figure 5.22 are divided by the footprint of the simulations to produce a discharge reduction per hectare ($m^3s^{-1}ha^{-1}$), which is displayed in Table 5.8. Looking at Table 5.8, the CSF scenario offers the most effective reduction in simulated mean peak discharge, this being $0.0058m^3s^{-1}ha^{-1}$. It is followed by hedgerow buffer strips and SCIMAP-Flood targeting. Although overall reduction was smaller, using these small land take targeting strategies was more efficient. Although these results cannot prove conclusively whether or not SCIMAP-Flood risk mapping is the best targeting approach, the results from Section 5.7.2.2 and the efficiencies displayed in Table 5.8 do indicate that SCIMAP-Flood is a suitable and useful tool for appraising multiple aspects of the catchment and will drive further investigation.

5.9   Recommendations

Land cover change alone has limited potential to deliver flood peak reductions in the Tutta Beck catchment. To achieve satisfactory mitigation, a significant reduction in mean peak discharge would have to be achieved. However, the largest potential reduction of $5.67m^3s^{-1}$, which was through blanket deciduous coverage, reduced peak flows by less than 10%. This means that complementary mitigation is likely to be required. As no internal flooding occurred during the observation window, the mitigation measures could be expected to have to withstand greater events to be deemed effective. This means that for land cover to be an effective mitigation approach for larger events, the peak flow reduction during the observation window would need to be greater than that simulated.

As these simulations could not be the only mitigation measure, even greater pressure is placed on the suitability of any land cover/management change strategies. This means that these would need to have minimal impact on agricultural function or offer an alternative mechanism for providing

income. To this end, the simulations that would be suitable for further investigation/incorporation into the grouped mitigation scenario would be:

- CSF woodland, in which third-party funding could compensate farmers;

- 25m deciduous buffer (land adjacent to a watercourse is difficult to exploit fully); and

- changes to arable land – adopting an overwinter cover crop or better land management with the support of third-party funding.

Chapter 6   Attenuation

6.1　Introduction

This chapter presents the results of different simulations with regard to targeting attenuation across the catchment to ascertain the most effective driver. Scenarios have been developed from a review of literature, fieldwork and stakeholder engagement. Physical interventions to slow or store water are preferred by stakeholders as they are more attractive to funders. Those features having an agricultural function and which provide flood mitigation are the most preferred; therefore, DoF structures and permanent ponds were considered for simulations.

Figure 6.1 shows the location of 11 attenuation simulations that were selected by reviewing all risk indicators. Table 6.1 shows the key risks for each location. Simulations will be assessed in isolation to ascertain the potential effectiveness and impact of each structure on discharge, with results used to generate grouped simulations. Section 6.2 details the results of topography-driven attenuation simulations and Section 6.3 reports the results of land cover-driven attenuation simulations. Section 6.4 explores the results of SCIMAP-Flood-driven attenuation simulations. Section 6.5 summarises the chapter and Section 6.6 summarises the recommendations for attenuation across the Tutta Beck catchment.
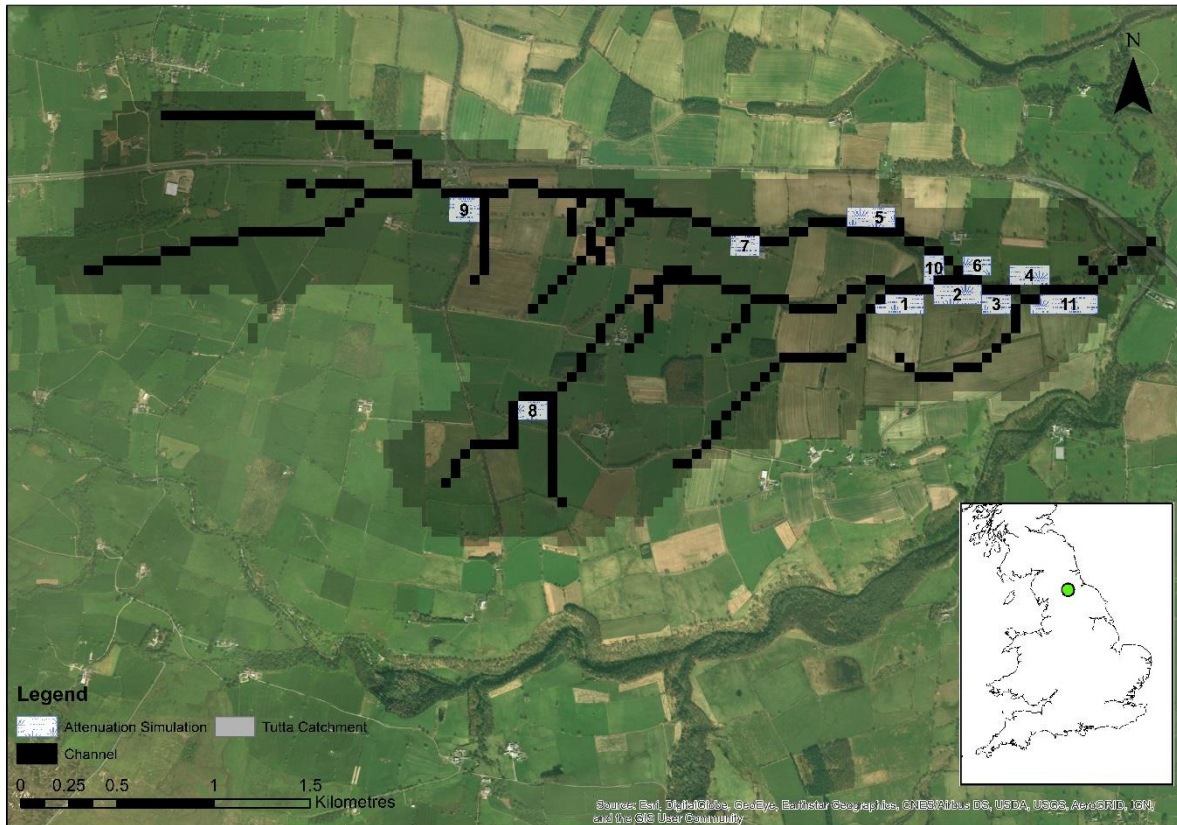
Figure 6.1 Map showing location of attenuation simulations throughout the Tutta Beck catchment. The numbers of the shapes denote the reference in Table 6.1.

Table 6.1 Rationale for each simulation and stakeholder feedback from scenario development discussions

Scenario number	Targeting rationale	Stakeholder suitable Y/N
1	Topography, land cover and SCIMAP-Flood	Y
2	Topography, land cover and SCIMAP-Flood	Y
3	Topography, land cover and SCIMAP-Flood	Y
4	Topography and SCIMAP-Flood	N
5	Land cover	N
6	Topography	N
7	Topography	N
8	Stakeholder	Y
9	Topography	Y
10	Land cover	N
11	Topography, land cover and SCIMAP-Flood	Y

6.2   Topography–driven attenuation simulations

Steep gradients increase the likelihood of runoff and the simulations displayed in Figure 6.2 show

the proximity of storage simulations to high-risk areas. Looking at Table 6.1, simulations 1, 2, 3, 4, 6,

7, 9 and 11 all denote areas with an increased risk of generating runoff because of the topography.
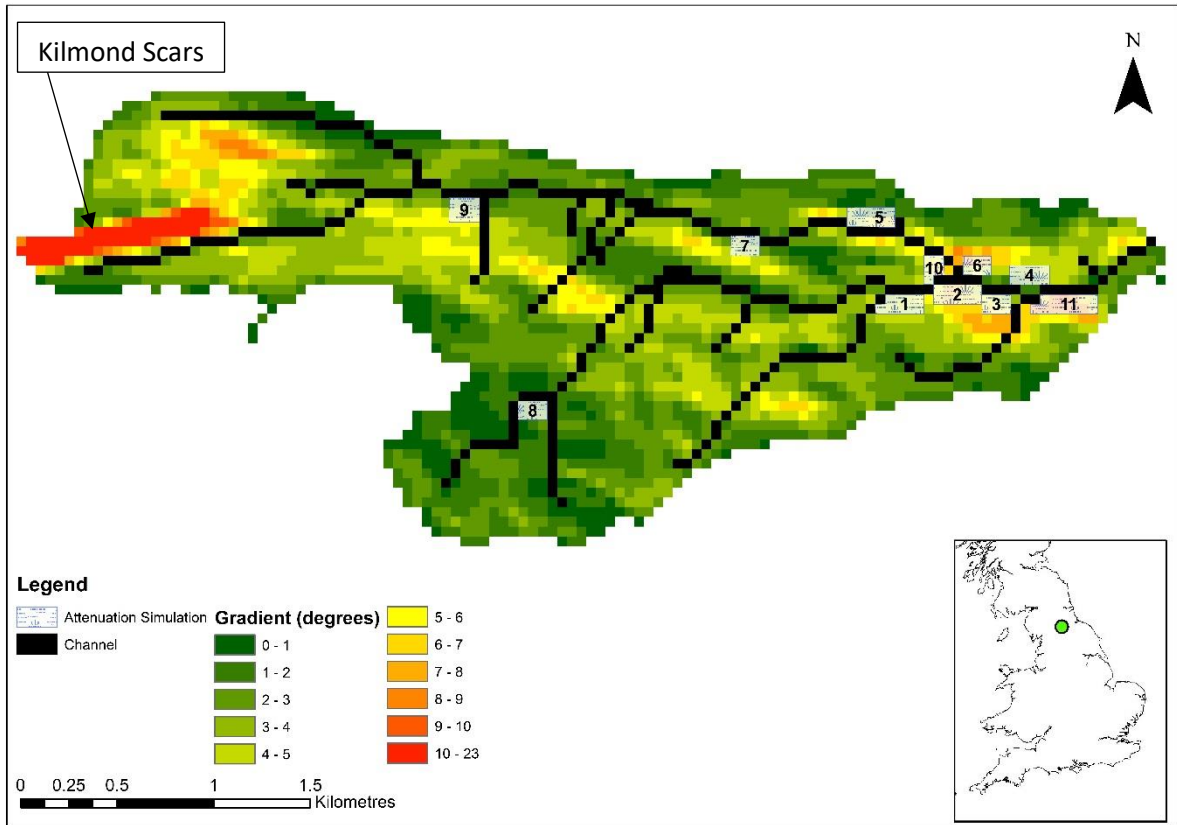
Figure 6.2 **Map showing gradients throughout the Tutta Beck catchment and location of simulations.**

6.2.1   Individual topography-driven attenuation simulations

Using Figure 6.2 and Table 6.1 the results of simulations that represent areas at risk of runoff

generated by topography are displayed below.
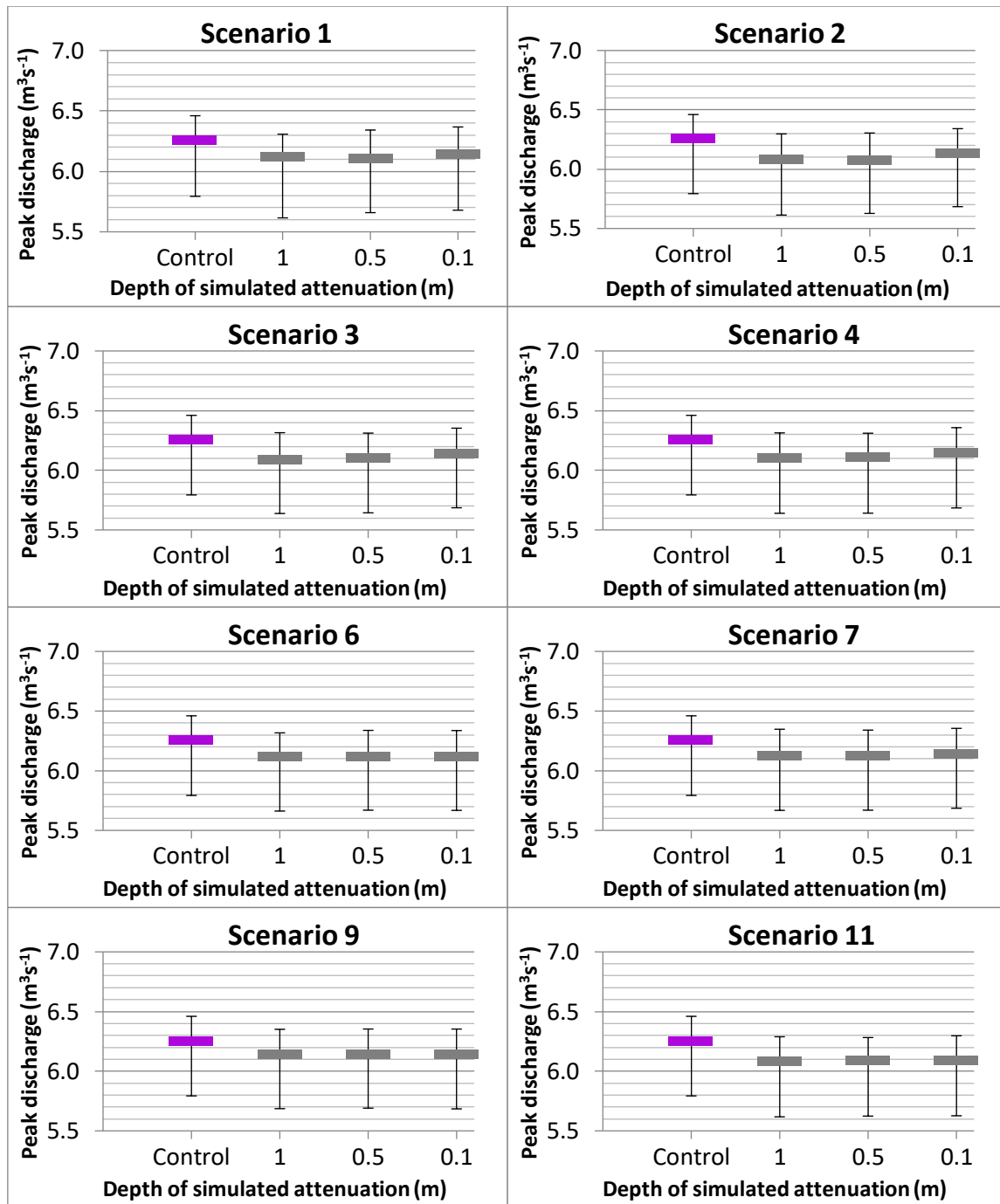
Figure 6.3 **Graph showing results of catchment attenuation sited in areas of elevated slopes. The X axis shows the depth of attenuation simulations, the Y axis the peak discharge from the simulations and the error bars the 90th and 10th percentile for the 25 individual model runs performed.**

The greatest reduction for a 1m-deep attenuation feature is through scenarios 2, 3 and 11, reducing

simulated mean peak flows to 6.08m^{3}s^{-1}, a 0.17m^{3}s^{-1} reduction. The greatest reduction for a 0.5m-

deep attenuation feature is through scenarios 2 and 11, which reduces simulated mean peak flows

to 6.08m^{3}s^{-1}, a 0.17m^{3}s^{-1} reduction. The greatest reduction for a 0.1m-deep attenuation feature is through Scenario 11, which reduces simulated mean peak flows to 6.09m^{3}s^{-1}, a 0.16m^{3}s^{-1} reduction.

All simulations offer a reduction so could be investigated depending on stakeholder desirability. The simulations were targeted at high slopes, where it would be feasible to insert attenuation. The area with gradients greater than 10°, Kilmond Scars, was not investigated as attenuation would not be deliverable.

Effective attenuation provides enough benefit in discharge to reduce risk with minimal land take and storage volume required. Therefore, looking at Figure 6.10, the change in discharge for required storage volume is compared for all locations. Of the topography-driven attenuation simulations, scenarios 3, 6, 7 and 9 have the smallest land take of 1.5ha, whereas Scenario 11 has the largest land take of 3.25ha.

Graphs like those shown in Figure 6.3 are produced from all model runs. These graphs and the data behind them are used to assess the impacts of attenuation. For subsequent sections the outputs from these graphs will be summarised in a table in the same format as Table 6.2.

Table 6.2 **Summary results of topography-driven attenuation simulations (units m^{3}s^{-1})**

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 6	Scenario 7	Scenario 9	Scenario 11
1m deep	6.12	6.08	6.08	6.10	6.12	6.13	6.14	6.08
0.5m deep	6.11	6.08	6.10	6.11	6.12	6.13	6.14	6.08
0.1m deep	6.15	6.14	6.14	6.14	6.12	6.14	6.14	6.09

6.2.2   Grouped topography-driven attenuation simulations

The use of multiple attenuation structures has several benefits, for example, targeting a different pathway and exceedance storage. Grouping the attenuation simulations displayed in Section 6.2.1 across equivalent depths of 1m, 0.5m and 0.1m can influence peak flows. The results are displayed in Figure 6.4 and Table 6.3.

Table 6.3 **Results of grouped topography-driven attenuation simulations**

Topography				
	Control	1m	0.5m	0.1m
Peak discharge 90th percentile (m^3s^{-1})	6.46	6.64	6.64	6.65
Upper peak discharge range (m^3s^{-1})	0.21	0.87	0.82	0.80
Mean peak discharge (m^3s^{-1})	6.25	5.76	5.82	5.86
Lower peak discharge range (m^3s^{-1})	0.46	0.47	0.47	0.49
Peak discharge 10th percentile (m^3s^{-1})	5.79	5.29	5.34	5.37
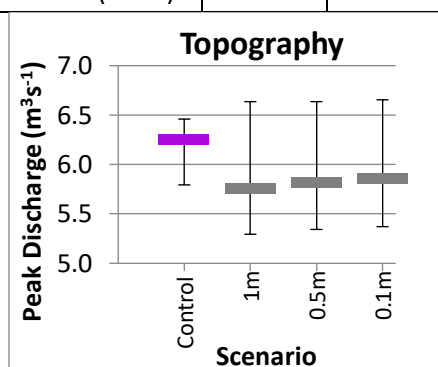
Figure 6.4 **Graph showing results of grouped topography-driven attenuation simulations.**

The greatest reduction from the grouped topography-driven simulations is from the deepest attenuation features, reducing simulated mean peak discharge to 5.76m^3s^{-1}, a 0.49m^3s^{-1} reduction. Table 6.3 shows the range of reductions in simulated mean peak discharge from the 0.1m–1m-deep features is minimal at 0.1m^3s^{-1}. The results show a large uncertainty with around 1.3m^3s^{-1} of variance.

A limitation of this scenario is that these features do not have a positive drainage connection so once full they cease to function or overtop. However, they could be positively drained to ensure a half drain down time of 24 hours (Anglian Water, 2011), which means the outflow from attenuation reduces impact on peak discharge, operates effectively for longer and can provide attenuation for a second event.

6.3 Arable land cover-driven attenuation simulations

Land cover influences runoff and Figure 6.5 shows attenuation simulations in relation to land cover. Land cover-driven attenuation simulations are targeted at arable land because it poses an increased

risk. This section investigates whether or not targeting arable land cover is suitable for use elsewhere.
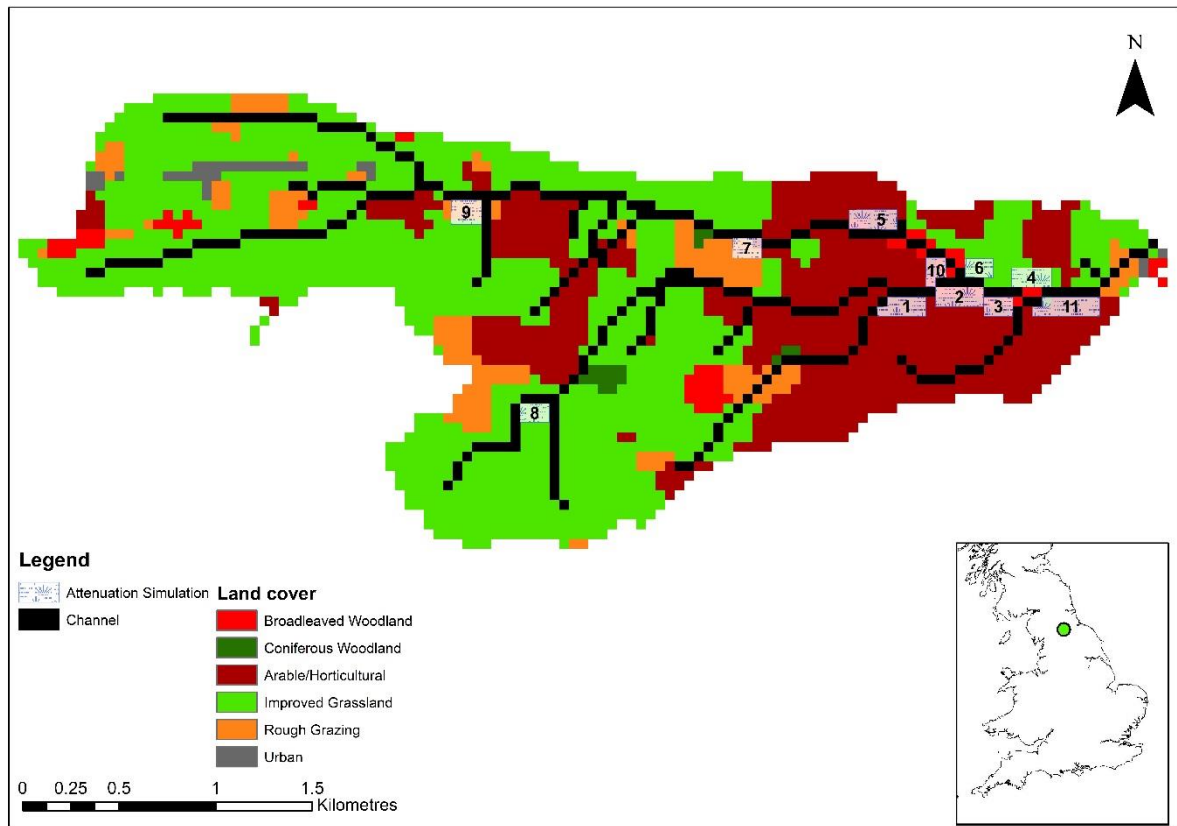
Figure 6.5 **Attenuation simulations overlaid on the LCM.**

6.3.1   Individual land cover-driven attenuation simulations

Looking at Figure 6.5 there are several simulations in arable fields. These simulations will assess the potential of attenuation targeted at arable land. To maximise the runoff captured, simulations are targeted at land adjacent to watercourses. The simulations that represent an increased risk to related land covers in Figure 6.5 are 1, 2, 3, 5, 10 and 11.

Table 6.4 **Results of catchment attenuation sited in areas of land cover with all simulations offering a reduction in peak flows**

	Scenario 1	Scenario 2	Scenario 3	Scenario 5	Scenario 10	Scenario 11
1m depth	6.12	6.08	6.08	6.12	6.14	6.08
0.5m depth	6.11	6.08	6.10	6.12	6.10	6.08
0.1m depth	6.15	6.14	6.14	6.12	6.11	6.09

All simulations offer a reduction in peak flow, so could be investigated depending on stakeholder desirability. Simulations were targeted at areas dominated by arable land; isolated arable fields in

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the upper catchment were not simulated due to the influence of improved grassland. The greatest

reductions for 1m-deep attenuation features were scenarios 2, 3 and 11, which reduced mean peak

discharge to 6.08m^{3}s^{-1}. The greatest reduction for a 0.5m-deep attenuation feature was provided by

scenarios 2 and 11, which reduced simulated mean peak discharge to 6.08m^{3}s^{-1}. The greatest

reduction for a 0.1m-deep feature was Scenario 11, which reduced simulated mean peak discharge

to 6.09m^{3}s^{-1}.

Effective attenuation provides enough benefit in discharge to reduce risk with minimal land take and

storage volume required. As such this single output is incorporated into in Figure 6.10, to compare

changes in discharge for all locations. Of the land cover-driven attenuation simulations, Scenario 10

has the smallest land take of 1.25ha, whereas Scenario 11 has the largest land take of 3.25ha.

6.3.2   Grouped land cover-driven attenuation simulations

The use of multiple attenuation structures has several benefits, for example, targeting a different

pathway and exceedance storage. Grouping the attenuation simulations from Section 6.3.1 across

equivalent depths of 1m, 0.5m and 0.1m can influence peak flows. The results are displayed in Figure

6.6 and Table 6.5.

Table 6.5 **Results of grouped land cover-driven attenuation simulations**

	Land cover			
	Control	0.1m	0.5m	1m
Peak discharge 90th percentile (m^{3}s^{-1})	6.46	6.12	6.11	6.07
Upper peak discharge range (m^{3}s^{-1})	0.21	0.23	0.24	0.23
Mean peak discharge (m^{3}s^{-1})	6.25	5.89	5.87	5.83
Lower peak discharge range (m^{3}s^{-1})	0.46	0.44	0.43	0.45
Peak discharge 10th percentile (m^{3}s^{-1})	5.79	5.45	5.44	5.38
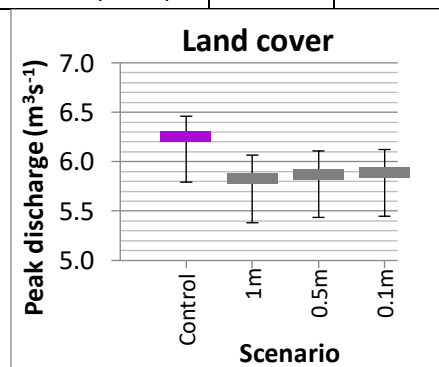
Figure 6.6 **Graph showing results of grouped land cover-driven attenuation simulations.**

The greatest reduction from the grouped land cover driven scenarios is from the deepest attenuation feature, which reduces simulated mean peak discharge to $5.83m^3s^{-1}$, a reduction of $0.42m^3s^{-1}$. Table 6.5 shows that the range of simulated mean peak discharge from the 0.1m–1m-deep features is minimal at $0.06m^3s^{-1}$. The results of this simulation show smaller uncertainty with variance of $0.6m^3s^{-1}$, giving some confidence in the potential effectiveness. As discussed in Section 6.2.2, a limitation of these simulations is a lack of positive drainage. This should, therefore, be investigated further at the detailed design stage.

6.4   SCIMAP-Flood-driven attenuation scenarios

Using risk mapping approaches can enable multiple conditions influencing runoff to be considered simultaneously across the catchment; isolated consideration of risk drivers may mean higher risks are missed. Using SCIMAP-Flood (Figure 6.7) it is possible to target areas exhibiting high risk across multiple datasets with high connectivity. To maximise the runoff captured, simulations are targeted at land adjacent to watercourses. Stakeholders suggest a preference for storage to be in proximity to watercourses or their fringe areas.
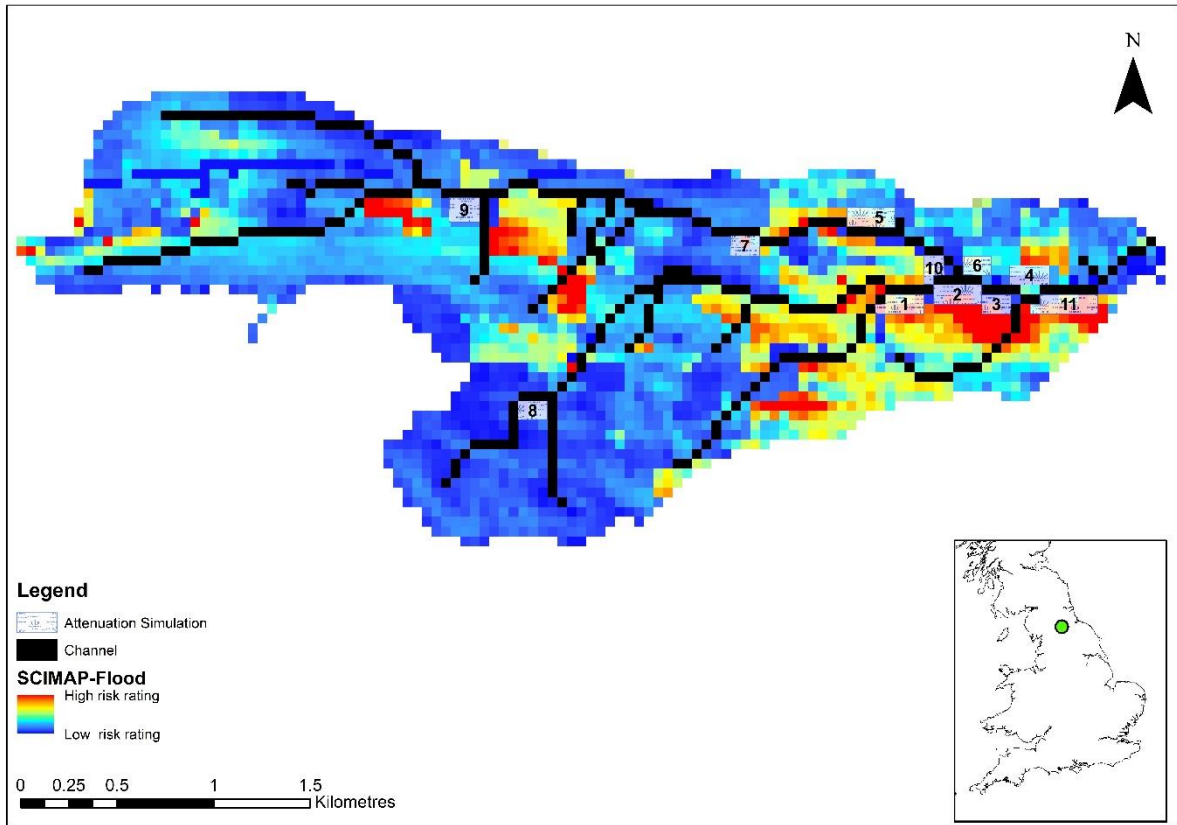
Figure 6.7 **Map of SCIMAP-Flood risk for the Tutta Beck catchment and the attenuation simulations developed to simulate interception.**

6.4.1   Individual SCIMAP-Flood-driven attenuation simulations

Looking at the map shown in Figure 6.7 there are several simulations that could be influenced by the SCIMAP-Flood high-risk areas. These simulations will be reviewed to assess the suitability of targeting attenuation using SCIMAP-Flood and the results are displayed in Table 6.6. The simulations that represent high-risk areas in Figure 6.7 are 1, 2, 3, 4, and 11.

Table 6.6 **Results of catchment attenuation drive by SCIMAP-Flood outputs (units are m^3s^{-1})**

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 11
1m depth	6.12	6.08	6.08	6.10	6.08
0.5m depth	6.11	6.08	6.10	6.11	6.08
0.1m depth	6.15	6.14	6.14	6.14	6.09

All simulations offer a reduction in simulated mean peak discharge so could be investigated depending on stakeholder desirability. The greatest reduction for a 1m-deep attenuation feature is found in scenarios 2, 3 and 11, which reduces simulated mean peak discharge to 6.08m^3s^{-1}. The greatest reduction for a 0.5m-deep attenuation feature is found in scenarios 2 and 11, which

reduces simulated mean peak discharge to 6.08m^{3}s^{-1}. The greatest reduction for a 0.1m-deep attenuation feature is Scenario 11, which reduces simulated mean peak discharge to 6.09m^{3}s^{-1}.

Effective attenuation provides enough benefit in discharge to reduce risk with minimal land take and storage volume required. Therefore, in Figure 6.10, the change in discharge for required storage volume is compared for all locations. Of the SCIMAP-Flood driven attenuation simulations, Scenario 3 has the smallest land take of 1.5ha, whereas Scenario 11 has the largest land take of 3.25ha.

6.4.2   Grouped SCIMAP-Flood-driven attenuation simulations

The use of multiple attenuation structures has several benefits, for example, targeting a different pathway and exceedance storage. Grouping the attenuation simulations displayed in Section 6.4.1 across equivalent depths of 1m, 0.5m and 0.1m can influence peak flows. The results are displayed in Figure 6.8 and Table 6.7.

Table 6.7 Results of grouped SCIMAP-Flood-driven attenuation simulations

SCIMAP-Flood				
	Control	0.1m	0.5m	1m
Peak discharge 90th percentile (m^3s^{-1})	6.46	6.10	6.07	6.02
Upper peak discharge range (m^3s^{-1})	0.21	0.21	0.24	0.24
Mean peak discharge (m^3s^{-1})	6.25	5.89	5.83	5.78
Lower peak discharge range (m^3s^{-1})	0.46	0.47	0.43	0.42
Peak discharge 10th percentile (m^3s^{-1})	5.79	5.42	5.40	5.36
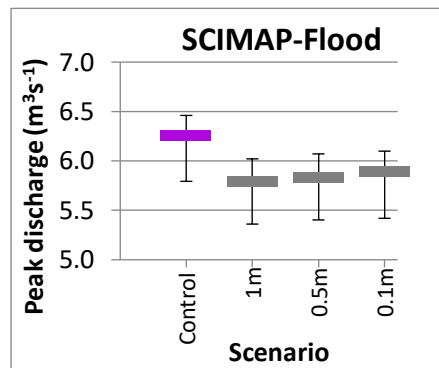
Figure 6.8 Graph showing results of grouped SCIMAP-Flood-driven attenuation simulations.

The greatest reduction of the grouped SCIMAP-Flood driven scenarios is from the deepest 1m

attenuation feature, which reduces simulated mean peak discharge to 5.78m^3s^{-1}, a reduction of

0.47m^3s^{-1}. Table 6.7 shows the range of reductions in simulated mean peak discharge from the

0.1m–1m deep features is minimal at 0.11m^3s^{-1}. The results of this simulation show lower variance of

around 0.67m^3s^{-1}, giving some confidence in its potential effectiveness. As discussed in Section 6.2.2,

the limitation of these simulations is a lack of positive drainage. This should, therefore, be further

investigated at the detailed design stage.

6.5   Summary

As displayed throughout this section, incorporating attenuation can deliver peak flow reductions

both through individual and grouped simulations. Topography-driven simulations offer the greatest

reduction in simulated mean peak discharge: 5.86m^3s^{-1} for 0.1m-deep attenuation; 5.82m^3s^{-1} for

0.5m-deep attenuation; and 5.76m^3s^{-1} for 1m-deep attenuation. These simulations show the largest

variance, reducing confidence in results. SCIMAP-Flood show the next greatest reductions: 5.89m^3s^{-1}

for 0.1m-deep attenuation; 5.83m^3s^{-1} for 0.5m-deep attenuation; and 5.78m^3s^{-1} for 1m-deep

attenuation. These simulations show lower variance, thereby providing greater confidence in results.

Targeting land cover shows the smallest reductions: 5.89m^{3}s^{-1} for 0.1m-deep attenuation; 5.87m^{3}s^{-1} for 0.5m-deep attenuation; and 5.83m^{3}s^{-1} for 1m-deep attenuation. These simulations show low variance, suggesting greater confidence in results.

Figure 6.9 and Table 6.8 display the summary statistics of the grouped simulations. Those targeted at land cover offer the most effective reduction for land take under all depth scenarios: 0.04m^{3}s^{-1}ha^{-1} under the 1m- and 0.5m-deep scenarios and 0.03m^{3}s^{-1}ha^{-1} under the 0.1m-deep scenario. At all depth scenarios both topography- and SCIMAP-Flood-driven simulations are 0.01m^{3}s^{-1}ha^{-1} less efficient than grouped land cover simulations. Table 6.8 shows the results of each individual simulation and the effect on mean peak discharge as well as effectiveness given the land take of each structure.

Table 6.8 **Results of the three grouped simulations including the summary statistics of reduction, land take and effectiveness**

	Control	1m-deep attenuation			0.5m-deep attenuation			0.1m-deep attenuation		
		LCM	Topo	SCIMAP-Flood	LCM	Topo	SCIMAP-Flood	LCM	Topo	SCIMAP-Flood
90th percentile (m^3s^{-1})	6.46	6.07	6.64	6.02	6.11	6.64	6.07	6.12	6.65	6.10
Upper range (m^3s^{-1})	0.21	0.23	0.87	0.24	0.24	0.82	0.24	0.23	0.80	0.21
Mean peak discharge (m^3s^{-1})	6.25	5.83	5.76	5.78	5.87	5.82	5.83	5.89	5.86	5.89
Lower range (m^3s^{-1})	0.46	0.45	0.47	0.42	0.43	0.47	0.43	0.44	0.49	0.47
10th percentile (m^3s^{-1})	5.79	5.38	5.29	5.36	5.44	5.34	5.40	5.45	5.37	5.42
Peak flow reduction (m^3s^{-1})		0.42	0.49	0.47	0.38	0.43	0.42	0.36	0.40	0.36
Area (hectares)		10.5	16	15.25	10.5	16	15.25	10.5	16	15.25
Effectiveness (flow reduction/land take) $m^3s^{-1}ha^{-1}$		0.04	0.03	0.03	0.04	0.03	0.03	0.03	0.02	0.02
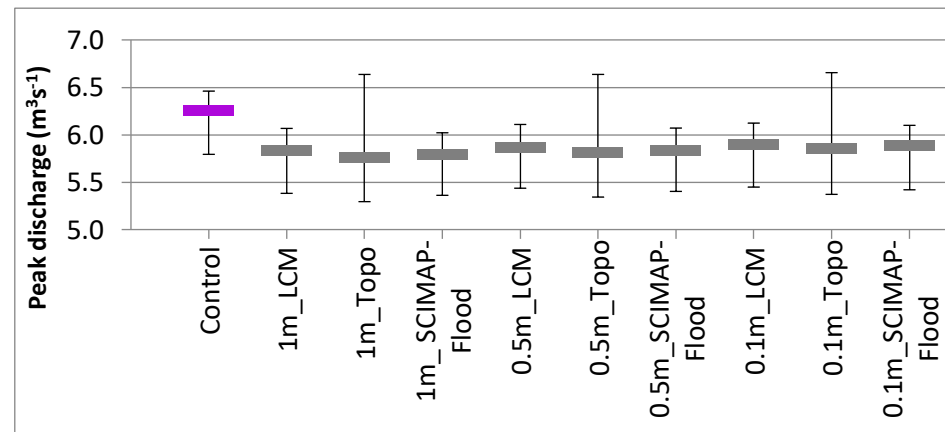
Figure 6.9 **Graph showing results of all grouped simulations for catchment attenuation.**

Table 6.9 **Results of all individual catchment attenuation simulations**

		Control	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11
	Land take (hectares)	0	2.25	2.5	1.5	2	2.5	1.5	1.5	1.5	1.5	1.25	3.25
1m depth	90th percentile (m^3s^{-1})	6.46	6.31	6.30	6.32	6.31	6.33	6.32	6.35	6.70	6.35	6.35	6.29
	Upper range (m^3s^{-1})	0.21	0.18	0.22	0.23	0.22	0.21	0.20	0.22	0.63	0.21	0.22	0.21
	Mean peak discharge (m^3s^{-1})	6.25	6.12	6.08	6.08	6.10	6.12	6.12	6.13	6.07	6.14	6.14	6.08
	Lower range (m^3s^{-1})	0.46	0.51	0.47	0.45	0.46	0.47	0.45	0.46	0.47	0.45	0.46	0.46
	10th percentile (m^3s^{-1})	5.79	5.62	5.61	5.64	5.64	5.65	5.66	5.67	5.60	5.69	5.68	5.62
	Sum of discharges 90th percentile (m^3)	4903.71	4895.68	4851.51	4864.13	4862.53	4878.40	4868.42	4884.06	4844.01	4891.83	4893.42	4845.86
	Sum of discharge mean (m^3)	4467.41	4456.73	4421.02	4437.79	4433.55	4450.51	4440.50	4447.10	4417.32	4462.32	4463.76	4410.04
	Sum of discharges 10th percentile (m^3)	3001.97	3001.60	2983.26	2995.01	2993.04	2994.2	3002.42	3008.68	2989.33	3010.55	3010.55	2978.72
	Peak flow reduction (m^3s^{-1})		0.13	0.17	0.17	0.15	0.13	0.14	0.13	0.18	0.11	0.12	0.17
	Effectiveness (flow reduction/land take) $m^3s^{-1}ha^{-1}$		0.06	0.07	0.11	0.08	0.05	0.09	0.08	0.12	0.08	0.09	0.05
0.5m depth	90th percentile (m^3s^{-1})	6.46	6.34	6.30	6.31	6.31	6.33	6.34	6.34	6.66	6.35	6.31	6.28
	Upper range (m^3s^{-1})	0.21	0.23	0.23	0.21	0.20	0.22	0.22	0.21	0.59	0.22	0.21	0.20
	Mean peak discharge (m^3s^{-1})	6.25	6.11	6.08	6.10	6.11	6.12	6.12	6.13	6.07	6.14	6.10	6.08
	Lower range (m^3s^{-1})	0.46	0.45	0.45	0.46	0.47	0.47	0.45	0.46	0.46	0.45	0.47	0.46
	10th percentile (m^3s^{-1})	5.79	5.66	5.63	5.64	5.64	5.64	5.67	5.67	5.61	5.69	5.62	5.62
	Sum of discharges 90th percentile (m^3)	4903.71	4895.99	4852.48	4868.29	4864.99	4879.84	4876.49	4885.71	4846.49	4892.81	4893.53	4847.40
	Sum of discharge mean (m^3)	4467.41	4463.72	4424.17	4435.21	4437.01	4451.27	4447.25	4453.94	4419.77	4455.51	4461.18	4412.69
	Sum of discharges 10th percentile (m^3)	3001.97	3021.03	2986.62	2995.12	2997.32	3009.62	3008.61	3012.68	2981.94	3016.03	3018.78	2977.04
	Peak flow reduction (m^3s^{-1})		0.15	0.18	0.15	0.15	0.14	0.13	0.12	0.18	0.12	0.15	0.17
	Effectiveness (flow reduction/land take) $m^3s^{-1}ha^{-1}$		0.06	0.07	0.10	0.07	0.05	0.09	0.08	0.12	0.08	0.12	0.05
0.1m depth	90th percentile (m^3s^{-1})	6.46	6.37	6.34	6.35	6.36	6.34	6.34	6.36	6.36	6.35	6.32	6.30
	Upper range (m^3s^{-1})	0.21	0.22	0.21	0.21	0.22	0.22	0.22	0.21	0.21	0.21	0.22	0.21
	Mean peak discharge (m^3s^{-1})	6.25	6.15	6.14	6.14	6.14	6.12	6.12	6.14	6.15	6.14	6.11	6.09
	Lower range (m^3s^{-1})	0.46	0.47	0.45	0.45	0.46	0.46	0.45	0.46	0.46	0.46	0.45	0.46
	10th percentile (m^3s^{-1})	5.79	5.68	5.68	5.69	5.68	5.66	5.67	5.69	5.68	5.68	5.66	5.63
	Sum of discharges 90th percentile (m^3)	4903.71	4892.84	4893.16	4894.22	4892.77	4883.75	4877.47	4893.69	4893.38	4893.54	4884.74	4849.85
	Sum of discharge mean (m^3)	4467.41	4462.82	4462.72	4463.36	4463.22	4456.25	4447.87	4462.70	4463.83	4463.55	4464.07	4413.64
	Sum of discharges 10th percentile (m^3)	3001.97	3016.88	3017.32	3014.77	3016.47	3010.12	3007.44	3016.79	3016.05	3014.57	2999.32	2980.06
	Peak flow reduction (m^3s^{-1})		0.11	0.12	0.11	0.11	0.13	0.13	0.11	0.10	0.11	0.15	0.16
	Effectiveness (flow reduction/land take) $m^3s^{-1}ha^{-1}$		0.05	0.05	0.08	0.06	0.05	0.09	0.07	0.07	0.07	0.12	0.05
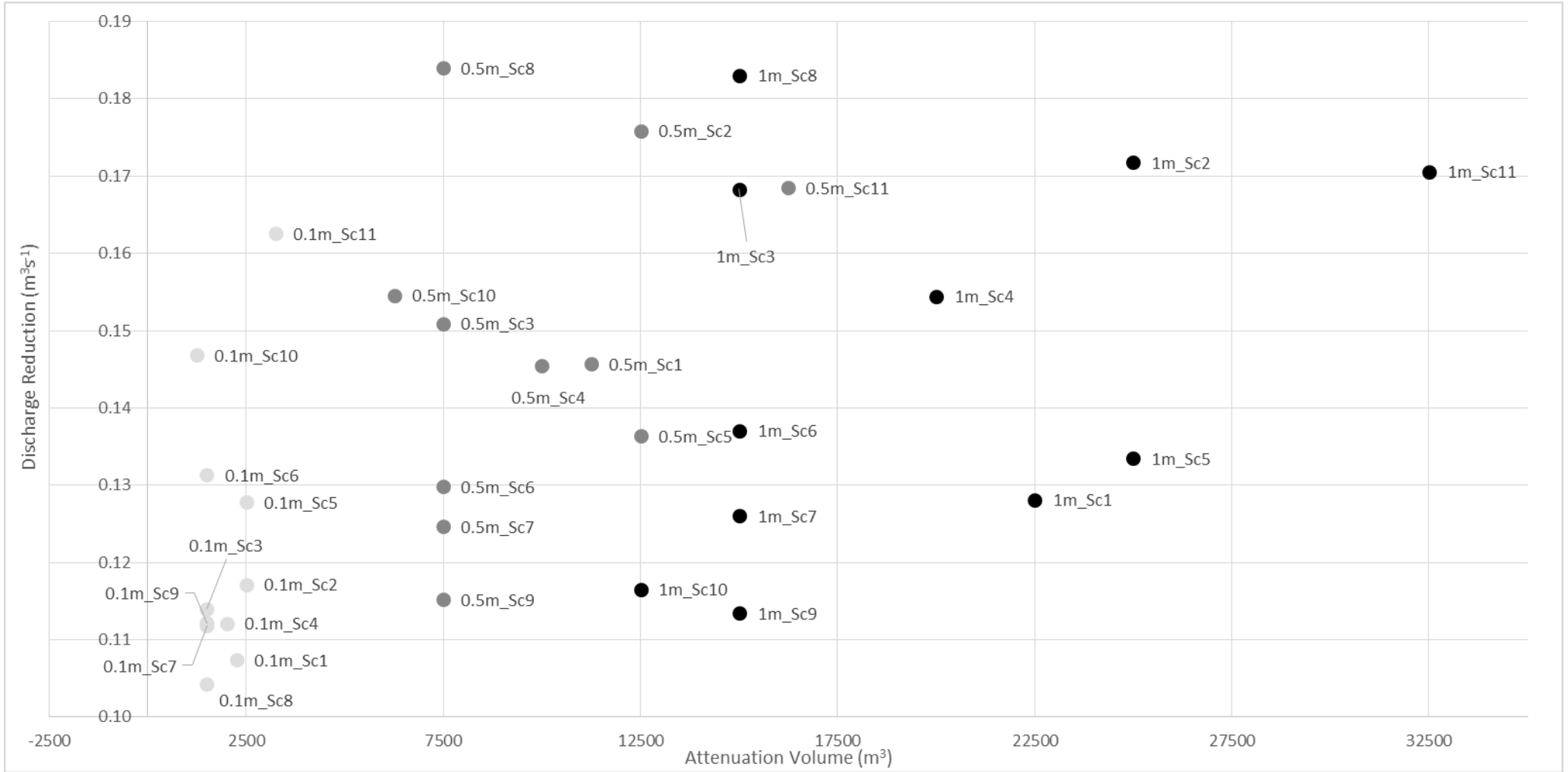
Figure 6.10 **Graph showing all individual attenuation simulations and displaying the mean peak discharge reduction for each simulation against the attenuation required to provide this reduction.**

All the attenuation simulations would not be acceptable due to the land take required. However, by designing features with positive drainage, storage volume could be reduced making features acceptable. At the detailed design stage, it may be possible to use interception techniques, such as a DoF or swales, to provide conveyance and storage.

The nature and resolution of CRUM3 outputs make it difficult for flood risk managers to justify a scheme and deliver a detailed design based solely on this technique. To better justify funding, a more detailed and higher resolution hydraulic modelling package will be required. Within this modelling approach conveyance structures, outfalls and storage can be simulated in detail to inform the design. Furthermore, such models can be used to simulate online storage features fed by the channel and not just features fed by overland flow.

6.6   Recommendations

Attenuation simulations in this chapter target interception of runoff. Constraints within CRUM3 prevent online simulations. Of the individual simulations, Scenario 8, driven by stakeholder suggestions, offered the largest reduction for 1m- and 0.5m-deep simulations and the most effective reduction per hectare, and this should be investigated further within the FAS. Scenario 10 also warrants further investigation due to high efficiency, although overall reduction was not as great as other simulations under the 1m and 0.5m scenarios. Scenario 11 offered some of the greatest reductions in mean peak flow; however, the large land take meant reduced effectiveness per hectare. Adjustments to the design of simulations may increase efficiency; however, this would be better increased by using higher resolution hydraulic modelling software.

Of the grouped simulations, those targeted at arable land use offered the most effective peak flow reduction and it is recommended that as part of a FAS attenuation and flow interception is targeted at these areas, specifically those locations in Section 6.3.2. This could be improved by using the more effective locations identified or improving the design of attenuation in the locations used in Section 6.3.2 areas to minimise land take.

In further combined simulations a new simulation driven by SCIMAP-Flood but only targeted at the

steep arable area in the south-east of the catchment will be used. The results are displayed in

Chapter 8.

Chapter 7   Assessing the Effects of In-Channel Flow Restrictions

7.1 Introduction

This chapter presents the results of different simulations with regard to ascertaining the most effective driver for targeting LWD. Scenarios are developed from a review of literature, fieldwork and stakeholder engagement. Stakeholders suggested that the use of LWD would be favourable in the FAS, partly due to acceptance of the technique within the funding processes. Figure 7.1 shows the 29 simulation locations across the catchment and Table 7.1 shows the upstream contributing area for each location.

LWD is most effective when it begins to restrict flow as discharge reaches a level at which flooding could occur; it would be ineffective to employ this method before a risk threshold is reached. LWD should not be used to impound significant volumes of flood water; therefore, only the first restriction that provides a measurable reduction in peak flow should be considered.

Table 7.1 **Catchment area for each flow restriction simulated across the catchment**

Reach ID	Catchment area (ha)	Reach ID	Catchment area (ha)	Reach ID	Catchment area (ha)
27	67.75	118	349.5	209	14.75
37	171.75	130	331.5	213	139
44	89.25	153	368	216	651
53	210.75	175	164.25	227	51.5
58	234.5	181	608.25	228	22
63	272.25	182	687.75	248	16.5
72	14	188	113.75	249	77.75
74	11	195	225.75	250	29.5
77	291.75	205	672.5	275	69.25
86	13	208	84.75		

The following sections discuss how LWD will be targeted. Each intervention will be simulated in isolation to ascertain effectiveness. Section 7.2 details the results of topography-driven flow restrictions and Section 7.3 reports the results of land cover-driven flow restrictions. Section 7.4 explains stakeholder- and fieldwork-driven simulations and Section 7.5 reports the results of SCIMAP-Flood-driven flow restrictions. Section 7.6 summarises the chapter and Section 7.7 presents recommendations for LWD.
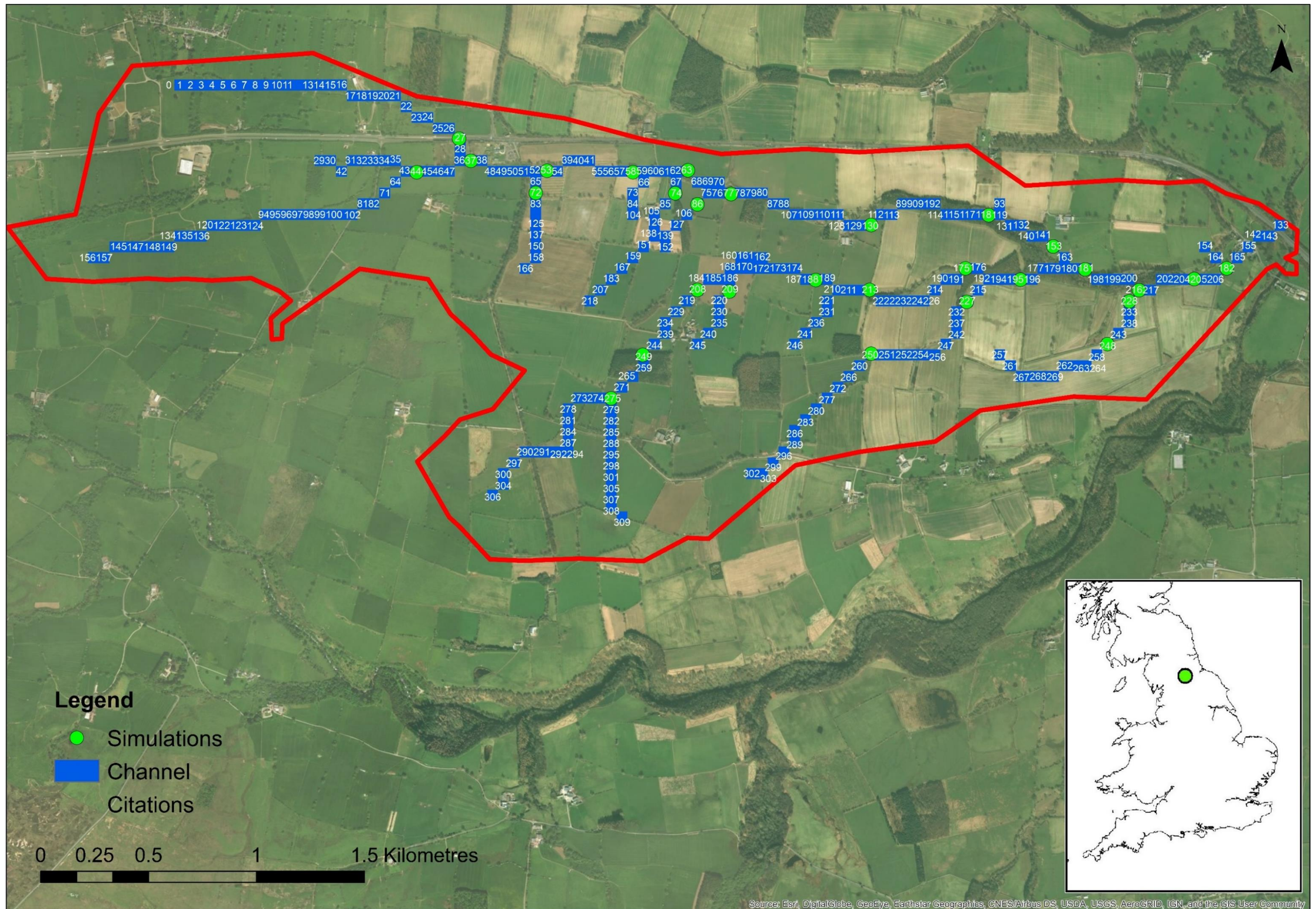
Figure 7.1 Map showing the individual reach ID used to site flow restrictions. The green points are the simulations applied across the catchment using a review of literature, fieldwork and stakeholder engagement. The numbering starts in the north-west (value 0) and is organised in rows west–east with the lowest values on the easternmost 'channel' cell of the southernmost row (value 309).

7.2   Topography-driven flow restrictions

Steep slopes increase the likelihood of runoff. This section identifies these areas of the catchment

and targets LWD dams at these channel reaches.

7.2.1   Hillslope runoff-driven flow restrictions

Figure 7.2 shows the gradients across the catchment. The red lines denote optimum locations for

interventions targeting this driver and the green circles show the locations used in simulations. Data

from points closest to red lines is used to represent flow restrictions targeted at hillslope gradients.
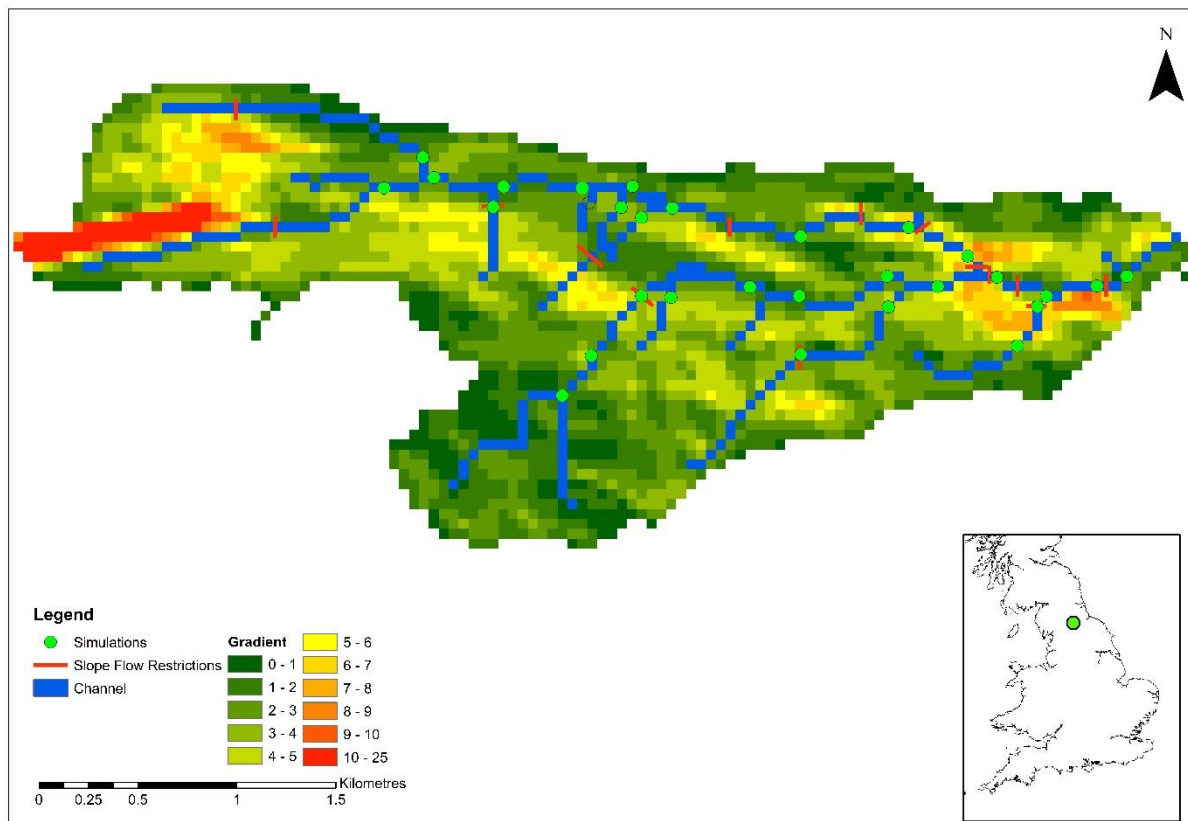
Figure 7.2 **Map showing hillslope runoff-driven flow restrictions. The red lines denote the key locations for flow restrictions and the green dots indicate where simulations have been performed.**

7.2.1.1   Individual hillslope runoff-driven flow restrictions

Figure 7.3 shows simulations from each location in a proximal location to the red lines in Figure 7.2.

Some interventions showed no reduction, suggesting timing of peak flows through these reaches

does not contribute to the peak flow itself.
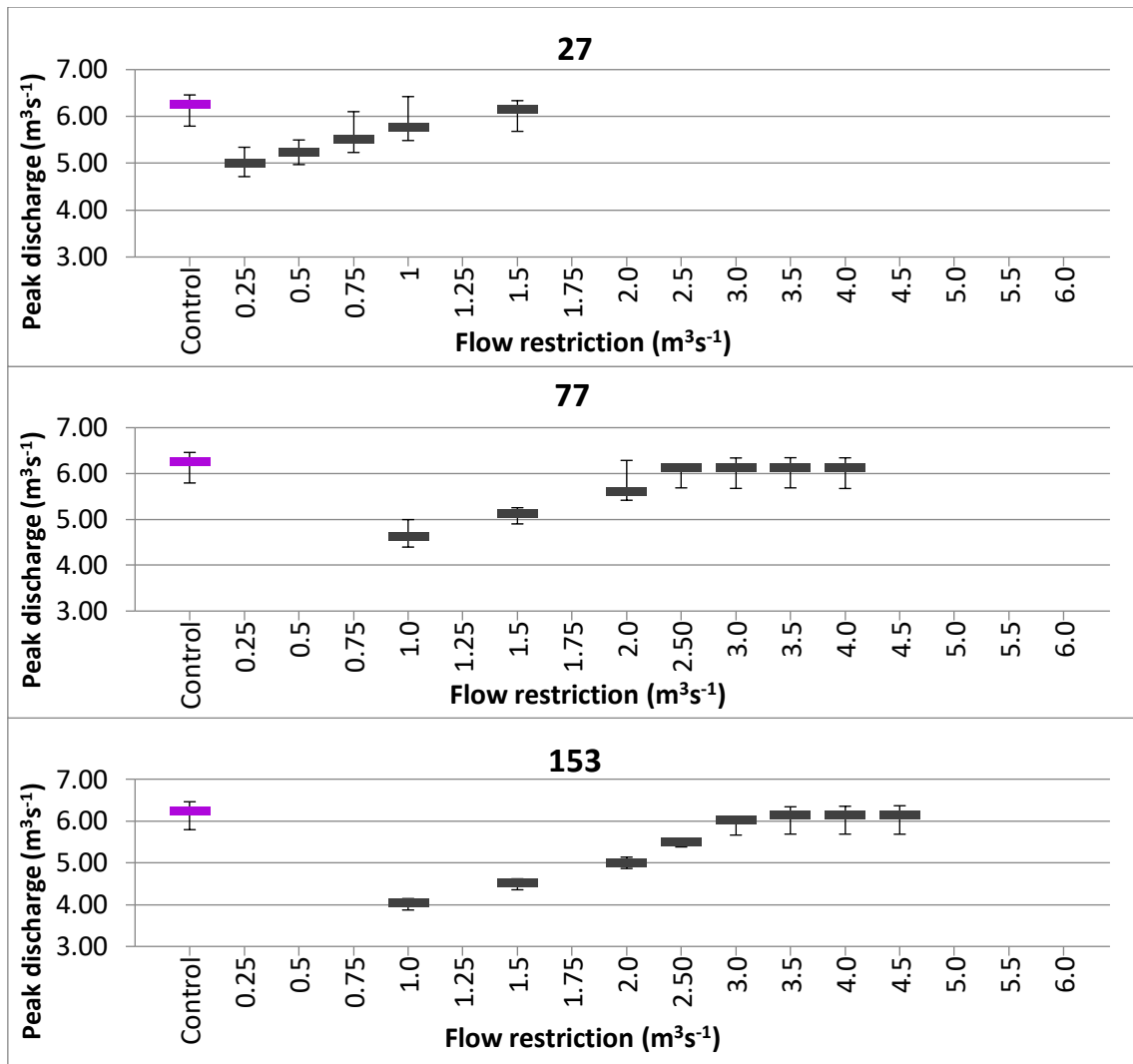
Figure 7.3 **Graph showing results of flow restriction simulations at reach IDs 27, 77 and 153. The X axis shows the restriction applied on the reach and the Y axis shows the simulated discharge.**

The simulations in Figure 7.3 show a measurable reduction in mean peak discharge. ID 27 is in the upper catchment and the first measurable reduction in mean peak flow occurs at a $1m^3s^{-1}$ flow restriction, which reduces the simulated discharge to $5.77m^3s^{-1}$. ID 77 is in the middle catchment and the first measurable reduction in mean peak flow occurs at a $2m^3s^{-1}$ flow restriction, which reduces simulated discharge to $5.60m^3s^{-1}$. ID 153 is in the lower catchment and the first measurable reduction in mean peak flow occurs at a $3m^3s^{-1}$ flow restriction, which reduces simulated discharge to $6.02m^3s^{-1}$.

Additional simulations to the three displayed were run; however, the results of these simulations showed no measurable reduction in mean peak discharge, suggesting they have minimal

contributions to peak flow. This could be because the timing of the discharge passing through these means it is not contributing to the peak flow event or because restrictions at these cells would not effectively restrict flow.

These simulation results suggest that flow restrictions targeted at watercourses adjacent to steep slopes could reduce discharge. However, using topography alone may not be effective because runoff and peak discharges are driven by several factors, including connectivity and the contributing drainage area. To conclusively demonstrate suitability or not would require a larger sample.

Graphs like those shown in Figure 7.3 are produced from all model runs. These graphs and the data behind them are used to select the key restriction for each reach ID simulated. For subsequent sections, the outputs from these graphs will be summarised in a table in the same format as Table 7.2.

Table 7.2 **Key restrictions for simulations at individual reach locations**

Table of restrictions			
Reach ID	ID 27	ID 77	ID 153
Restriction applied	$1m^3s^{-1}$	$2m^3s^{-1}$	$3m^3s^{-1}$

7.2.1.2   Grouped hillslope runoff-driven flow restrictions

The three reaches from Section 7.2.1.1 that reduced simulated mean peak flow are grouped into one simulation into which multiple flow restrictions targeted at hillslope elevations are inserted.
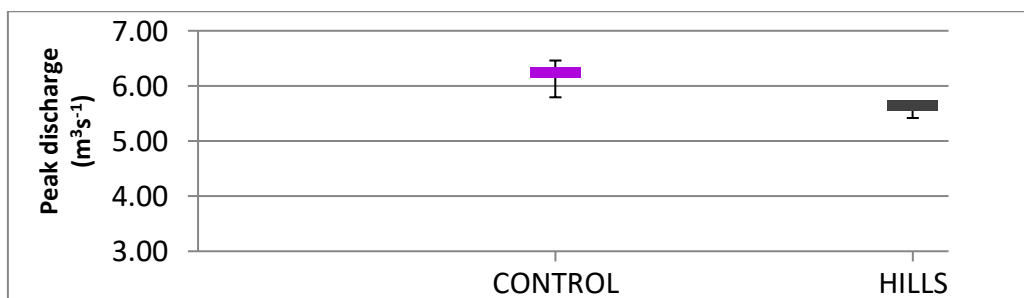
Figure 7.4 **Graph showing results of hillslope runoff-driven flow restrictions as per Table 7.2.**

This simulation reduced mean peak discharge to $5.63m^3s^{-1}$, a $0.62m^3s^{-1}$ reduction. There was only a small variation ($0.28m^3s^{-1}$) from the mean, suggesting confidence in the effectiveness of this

particular simulation, which produces an average reduction per barrier of 0.21m^{3}s^{-1}. The result of

this simulation is not as much as the sum of each intervention and this could be because upstream

restrictions reduce the flow that reaches downstream restrictions. This action could be beneficial by

reducing the pressure on downstream interventions and providing storage for exceedance events.

7.2.2 Channel gradient-driven flow restrictions

Steep channels can generate high velocities of water with high erosivity, incision and rapid onset of

peak flows, as well as increasing in-channel conveyance. Targeting LWD at these areas could be

beneficial for mitigating flood risk. Figure 7.5 shows the channel gradients for the Tutta Beck

catchment, the locations of which are displayed with pink lines crossing the channel.
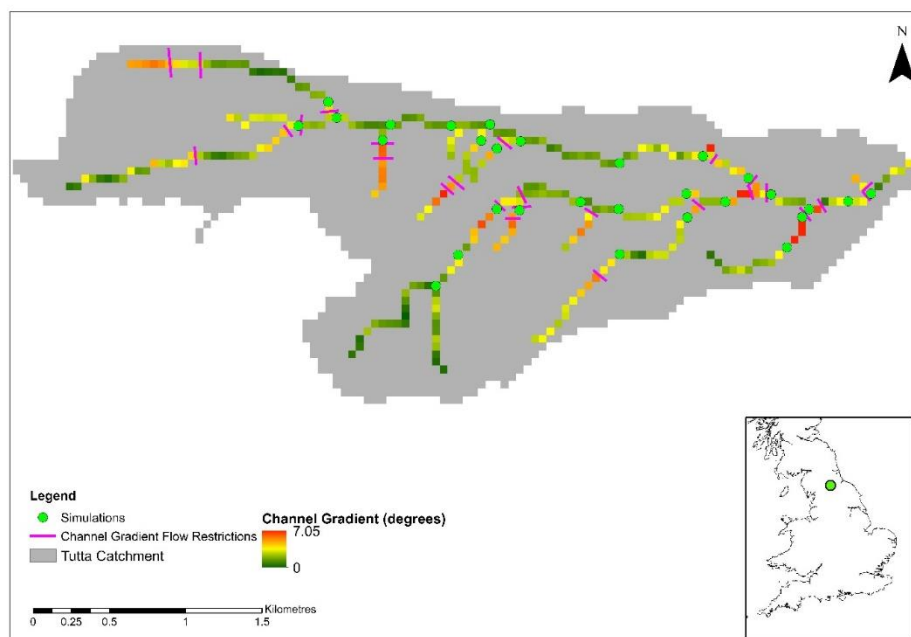
Figure 7.5 **Map showing the areas across the Tutta Beck catchment's channel network with elevated gradients and the proximity of flow restriction simulations to these areas.**

7.2.2.1 Channel gradient-driven flow restrictions

The simulations from Figure 7.5 that generated the most suitable reduction in peak flow are

displayed in Table 7.3. All simulations in Table 7.3 show a measurable reduction in peak flow. Some

interventions showed no reduction, suggesting timing of peak flows through these reaches does not

contribute to the peak flow itself.

Table 7.3 **Optimum channel gradient-driven flow restrictions**

Table of restrictions							
Reach ID	**27**	**37**	**77**	**182**	**208**	**213**	**216**
Restriction (m^3s^{-1})	1	1	2	5.5	0.5	1	5.5
Reduction in peak flow (m^3s^{-1})	5.77	5.77	5.60	5.69	5.94	1	5.53

Using steep channel gradients alone may not be effective because peak flows are influenced by several variables. Steep reaches commonly have narrower floodplains and less storage opportunity along the channel length. To conclusively assess the suitability of using elevated slope gradients to target flow restrictions a larger sample would be required.

7.2.2.2   Grouped channel gradient-driven flow restrictions

The reaches from Section 7.2.2.1 that reduced simulated mean peak flow are grouped into one simulation into which multiple flow restrictions targeted at channel gradients are inserted.

Table of restrictions							
Reach ID	**27**	**37**	**77**	**182**	**208**	**213**	**216**
Restriction (m^3s^{-1})	1	1	2	5.5	0.5	1	5.5

Figure 7.6 **Graph showing results of channel gradient-driven flow restrictions according to table of restrictions above.**

This simulation reduced mean peak discharge to $5.42m^3s^{-1}$, a $0.83m^3s^{-1}$ reduction, with a small variation from the mean of $0.27m^3s^{-1}$ between the 10th and 90th percentile. It used seven barriers, which produced an average reduction per barrier of $0.12m^3s^{-1}$. The result of this simulation is not as much as the sum of each intervention and this could be because upstream restrictions reduce the flow that reaches downstream restrictions. This action could be beneficial by reducing the pressure on downstream interventions and providing storage for exceedance events.

7.2.3   Grouped hillslope runoff- and channel gradient-driven flow restrictions

In this section, all topography-driven interventions in sections 7.2.1 and 7.2.2 that reduced simulated peak flow are used in a grouped simulation to ascertain the potential cumulative benefits.

Table of restrictions								
Reach ID	27	37	77	153	182	208	213	216
Restriction (m^3s^{-1})	1	1	2	3	5.5	0.5	1	5.5

Figure 7.7 **Graph showing results of both hillslope runoff- and channel gradient-driven flow restrictions according to table of restrictions above.**

This simulation reduced mean peak discharge to 5.43m^3s^{-1}, a 0.83m^3s^{-1} reduction, and shows a small variation from the mean of 0.26m^3s^{-1} between the 10th and 90th percentile. It used eight barriers and produced an average reduction per barrier of 0.10m^3s^{-1}. The result of the grouped simulations is not as effective as each individual restriction from sections 7.2.1 and 7.2.2 added together. This could be because simulations are along the same channel and, therefore, upstream restrictions reduce the flow that reaches downstream barriers. This, however, reduces the flow rate to downstream barriers, which reduces pressure and also reduces the attenuation requirement of each flow restriction.

7.2.4   Summary of topography-driven flow restrictions

As can be seen in sections 7.2.1, 7.2.2 and 7.2.3, the insertion of flow restrictions can have a varied impact on peak flows throughout the catchment. Using topography to target flow restrictions is one method that could be investigated further. However, some results do not exhibit reductions and this could be down to other catchment conditions mitigating impacts.

7.3   Land cover-driven flow restrictions

Some land covers can increase the likelihood of runoff generation and the following restrictions are targeted at mitigating the impact of land cover on hydrology. This section identifies the areas of the catchment with land covers susceptible to generating runoff and targets LWD dams at associated channel reaches. Figure 7.8 shows the land cover types across the catchment: blue symbols denote suitable locations for mitigating the risk of runoff from high-risk land covers; white circles denote the locations of simulations performed with many being transferable.
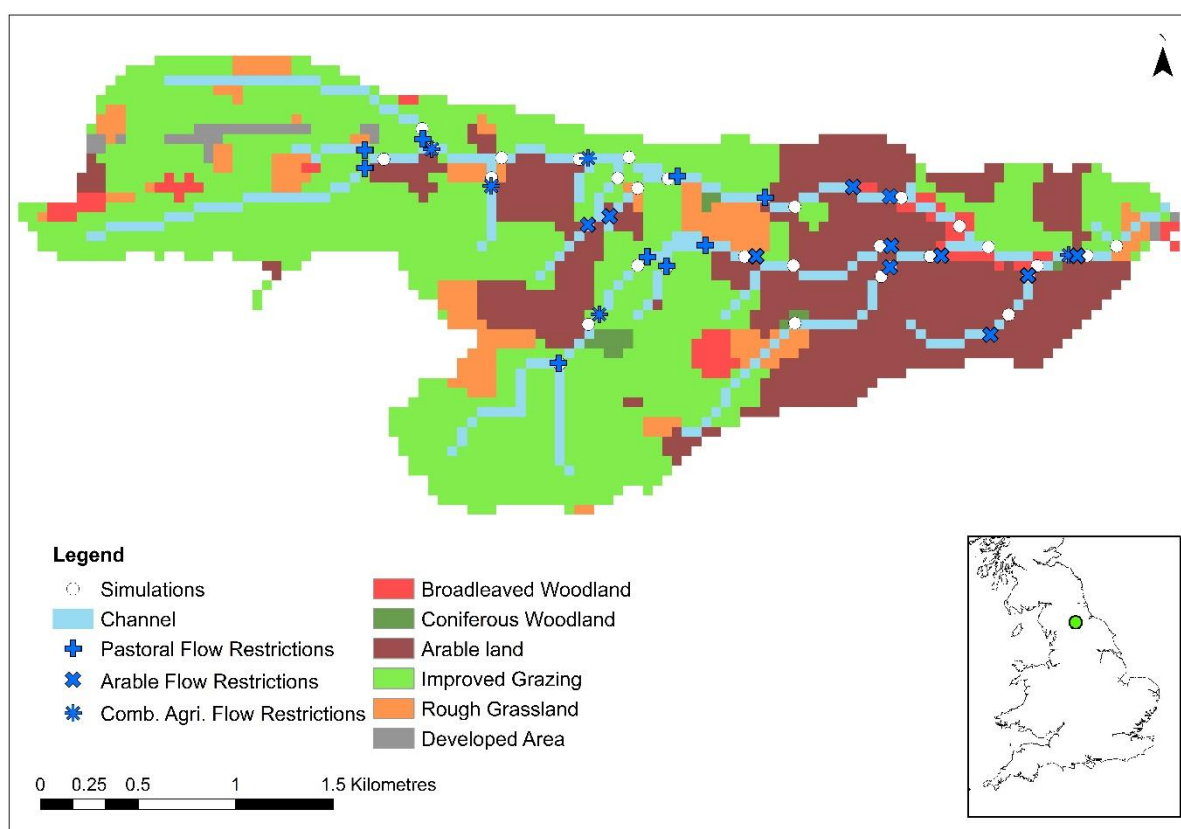
Figure 7.8 **Map showing land cover for the Tutta Beck catchment with simulation locations and high-risk areas to target.**

7.3.1   Arable land-driven flow restrictions

This section investigates the suitability of targeting LWD interventions at arable land and the potential impact on simulated mean peak discharge. The arable areas are predominantly to the east of the catchment with only one watercourse having a solely arable catchment.

7.3.1.1 Individual arable land-driven flow restrictions

Looking at the simulations shown in Figure 7.8, there are a number that could be influenced by runoff from arable fields and these will be reviewed to assess the potential for targeting flow restrictions at watercourses adjacent to arable land. The results are displayed in Table 7.4.

Table 7.4 Results of optimum arable land-driven flow restrictions

Table of restrictions		
Reach ID	ID 175	ID 195
Restriction applied	$1m^3s^{-1}$	$1.5m^3s^{-1}$
Reduction in peak flow (m^3s^{-1})	5.75	5.64

The simulations in Table 7.4 show a measurable reduction in peak flow and the results displayed in this section show that simulations targeted at watercourses running through arable land could yield simulated reductions in mean peak flow. However, targeting restrictions at land cover may not be effective because runoff generation requires certain factors, such as topography, to develop connectivity to watercourses. To conclusively assess the suitability of targeting flow restrictions at arable land a larger sample would be required.

7.3.1.2 Grouped arable land-driven flow restrictions

From the simulations in Figure 7.8, the following results show the impact that targeting flow restrictions at simulations 175 and 195 could have on peak discharge.

Table of restrictions		
Reach ID	ID 175	ID 195
Restriction applied	$1m^3s^{-1}$	$1.5m^3s^{-1}$
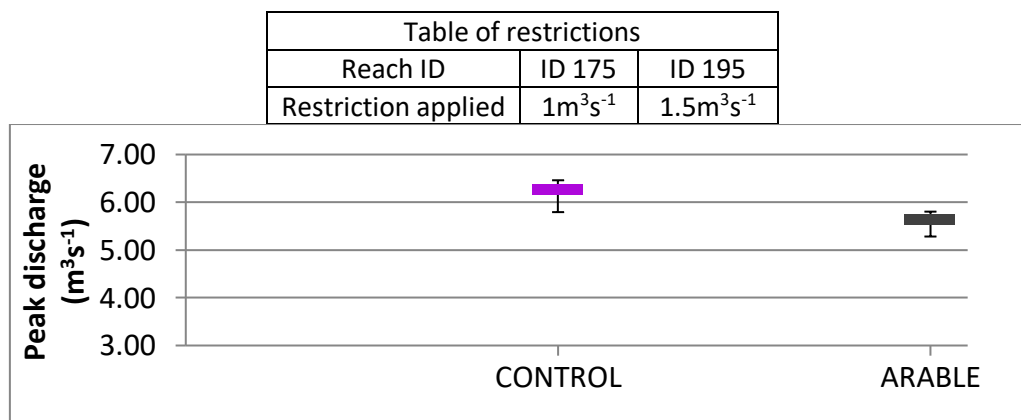
Figure 7.9 Graph showing results of arable land-driven flow restrictions according to table of restrictions above.

This simulation reduced mean peak discharge to $5.64m^3s^{-1}$, a $0.61m^3s^{-1}$ reduction, with a $0.53m^3s^{-1}$ variation from the mean between the 10th and 90th percentile. It used two barriers and produced

an average reduction per barrier of 0.31m^3s^{-1}. The result of this grouped simulation is not as effective as each individual restriction from Section 7.3.1.1 added together. This could be because simulations are along the same channel and, therefore, upstream restrictions reduce the flow that reaches downstream barriers. This action, however, reduces the flow rate to downstream barriers, which reduces pressure and also reduces the attenuation requirement of each flow restriction.

7.3.2 Improved grassland-driven flow restrictions

This section investigates the suitability of targeting LWD interventions at improved grassland and the potential impact on simulated mean peak discharge. The improved grassland areas are predominantly to the west of the catchment and include several channel headwaters.

7.3.2.1 Individual improved grassland-driven flow restrictions

There are several simulations displayed in Figure 7.8 that could be influenced by runoff from improved grassland fields. Table 7.5 shows the results of optimum flow restrictions applied at different reaches. Some interventions showed no reduction, suggesting timing of peak flows through these reaches does not contribute to the peak flow itself.

Table 7.5 **Results of optimum improved grassland-driven flow restrictions**

Table of restrictions			
Reach ID	ID 27	ID 188	ID 208
Restriction applied	1m^3s^{-1}	0.75m^3s^{-1}	0.5m^3s^{-1}
Reduction in peak flow (m^3s^{-1})	5.77	5.91	5.94

The simulations in Table 7.5 all show a measurable reduction in peak flow through the insertion of flow restrictions. These results show that simulations targeted at watercourses running through improved grassland land can yield simulated reductions in mean peak flow. However, targeting flow restrictions at land cover may not be effective because runoff requires certain other factors, such as topography, to develop connectivity to watercourses. To conclusively assess the suitability of targeting flow restrictions at improved grassland a larger sample would be required.

7.3.2.2 Grouped improved grassland-driven flow restrictions

Looking at the simulations in Figure 7.8, the following results show the impact that targeting flow restrictions at all watercourses adjacent to improved grassland could have on peak discharge.

Table of restrictions			
Reach ID	ID 27	ID 188	ID 208
Restriction applied	$1m^3s^{-1}$	$0.75m^3s^{-1}$	$0.5m^3s^{-1}$
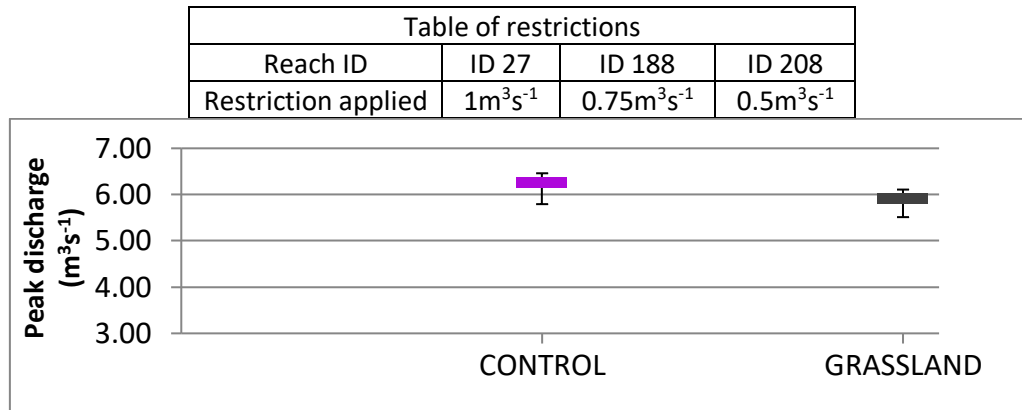
Figure 7.10 **Graph showing results of improved grassland-driven flow restrictions according to table of restrictions above.**

This simulation reduced mean peak discharge to $5.91m^3s^{-1}$, a $0.34m^3s^{-1}$ reduction, with a variation from the mean of $0.59m^3s^{-1}$ between the 10th and 90th percentile. It used three barriers and produced an average reduction per barrier of $0.11m^3s^{-1}$. The result of this grouped simulation is not as effective as each individual restriction from Section 7.3.2.1 added together. This could be because simulations are along the same channel and, therefore, upstream restrictions reduce the flow that reaches downstream barriers. This action, however, reduces the flow rate to downstream barriers, which reduces pressure and also reduces the attenuation requirement of each flow restriction.

7.3.3 Combined agricultural land-driven flow restrictions

This section investigates the potential impact that targeting flow restriction at watercourses adjacent to both arable land and improved grassland could have on peak flow.

7.3.3.1 Individual combined agricultural land-driven flow restrictions

The following results show flow restrictions that are targeted to areas that receive inflows from a combination of arable land and improved grassland.

Table 7.6 Results of optimum combined agricultural land-driven flow restrictions

Table of restrictions						
Reach ID	ID 53	ID 63	ID 118	ID 182	ID 204	ID 208
Restriction applied	$1.5m^3s^{-1}$	$2m^3s^{-1}$	$2.5m^3s^{-1}$	$5.5m^3s^{-1}$	$5.5m^3s^{-1}$	$0.5m^3s^{-1}$
Reduction in peak flow (m^3s^{-1})	5.90	5.81	5.60	5.69	5.82	5.94

The simulations in Table 7.6 all show a measurable reduction in peak flow through the insertion of flow restrictions. Results displayed in this section show that simulations targeted at watercourses running through general agricultural land can yield simulated reductions in mean peak flow. Targeting restrictions at land cover may not be effective because runoff requires other factors, such as topography, to develop the connectivity to watercourses that can increase speed of response of the downstream hydrograph. To conclusively assess the suitability of targeting flow restrictions at arable land a larger sample across several catchments would be required. A further consideration with regard to the simulations targeted at land cover is that the Tutta Beck catchment is almost entirely agricultural, so there is insufficient data to compare different land covers. In a larger catchment with sub-catchments dominated by different land covers it may feasible to do this.

7.3.3.2 Grouped agricultural land-driven flow restrictions

Using the individual location outputs in Section 7.3.1.1, the following section shows the results of groups of restrictions targeted to areas that receive inflows from a combination of arable land and improved grassland.

Table of restrictions						
Reach ID	ID 53	ID 63	ID 118	ID 182	ID 204	ID 208
Restriction applied	$1.5m^3s^{-1}$	$2m^3s^{-1}$	$2.5m^3s^{-1}$	$5.5m^3s^{-1}$	$5.5m^3s^{-1}$	$0.5m^3s^{-1}$

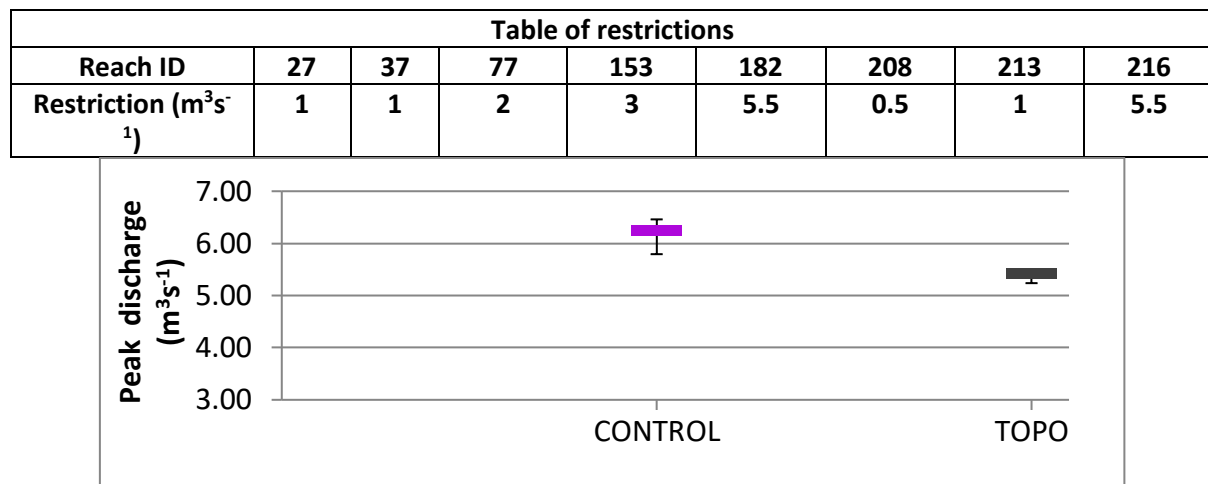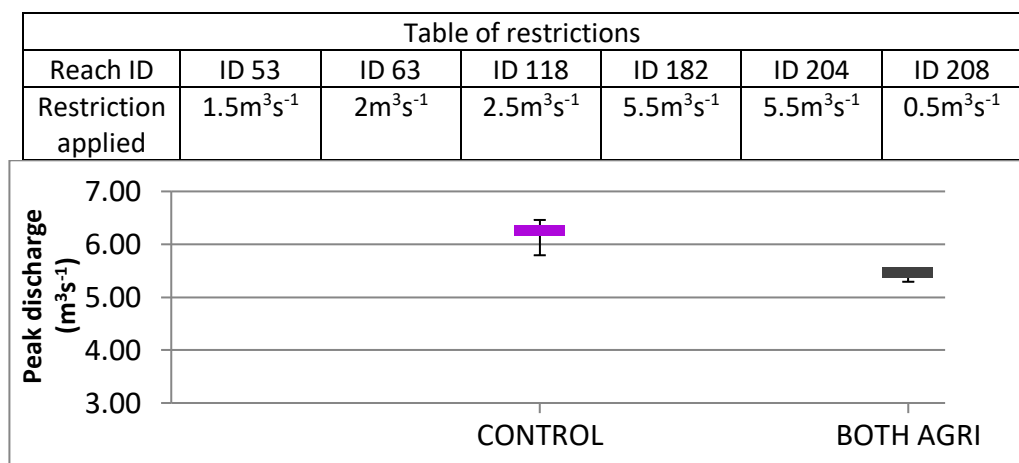**_Figure 7.11_ Graph showing results of agricultural land-driven flow restrictions according to table of restrictions above.**

This simulation reduced mean peak discharge to $5.47m^3s^{-1}$, a $0.78m^3s^{-1}$ reduction, with a variation from the mean of $0.21m^3s^{-1}$ between the 10th and 90th percentile. It used six barriers and produced an average reduction per barrier of $0.13m^3s^{-1}$. The result of this grouped simulation is not as effective as each individual restriction from Section 7.3.3.1 added together. This could be because simulations are along the same channel and, therefore, upstream restrictions reduce the flow that reaches downstream barriers. This action, however, reduces the flow rate to downstream barriers, which reduces pressure and also reduces the attenuation requirement of each flow restriction.

7.3.4   Summary of land cover-driven flow restrictions

Any agricultural land cover could be suitable as a target for flow restrictions because under certain conditions it can generate runoff. Such a conclusion could not be drawn from this study due to a lack of other land uses to compare data against and the overwhelming influence that agricultural land has on the hydrological regime of this catchment. In an agriculture-dominated catchment such as Tutta Beck, it may be more suitable to investigate the harvests and crop rotations as part of an agricultural management programme to improve spatial targeting. The main outcome from these results is that further assessment of the catchment-scale influence of land covers is required but taking into account other factors, such as slope or relative time, which could have an influence on peak discharge.

7.4   Stakeholder- and fieldwork-driven flow restrictions

Meetings with stakeholders made it clear there was a requirement for measures to achieve a clear cost-benefit relationship and for the reduction in peak flows to be calculable. The investigations in this section are deemed desirable from the results of stakeholder engagement.

7.4.1   Confluence-driven flow restrictions

Targeting flow restrictions near confluences was highlighted as an option by stakeholders. The rationale for this was that by inserting one barrier, two watercourses could be intercepted. Furthermore, many of the confluences in the Tutta Beck catchment are in wooded or unused areas,

thereby minimising their impact on agriculture. Figure 7.12 shows the proximity of simulations and confluences. In some instances, flow restrictions have been simulated further down from the confluences.
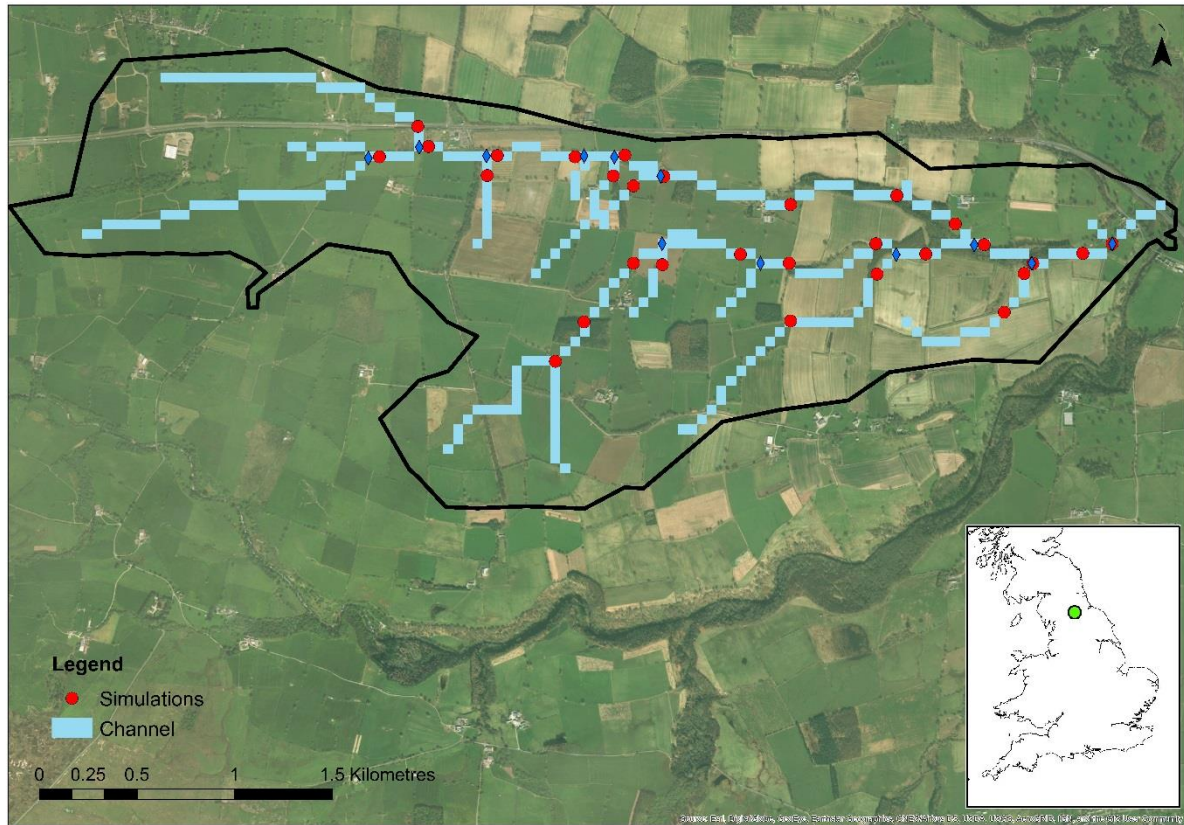
Figure 7.12 **Map showing location of confluence-driven flow restrictions and the simulations chosen for review across the catchment.**

7.4.1.1 Individual confluence-driven flow restrictions

The section describes simulations of flow restrictions targeted at confluences. These simulations are to ascertain whether or not installing flow restrictions at confluences could deliver peak flow reductions.

Table 7.7 **Results of optimum confluence-driven flow restrictions**

Table of restrictions						
Reach ID	ID 37	ID 53	ID 63	ID 195	ID 204	ID 216
Restriction applied	$1m^3s^{-1}$	$1.5m^3s^{-1}$	$2m^3s^{-1}$	$1.5m^3s^{-1}$	$5.5m^3s^{-1}$	$5m^3s^{-1}$
Reduction in peak Flow (m^3s^{-1})	5.77	5.90	5.81	5.64	5.82	5.53

The simulations in Table 7.7 all show a measurable reduction in peak flow through the insertion of flow restrictions. This is in accordance with the desirability of this type of mitigation measure as

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outlined by stakeholders and would be hydrologically effective as well as being economically viable because of the interventions being on unused or low-value land.

7.4.1.2 Grouped confluence-driven flow simulations

Looking at the simulations in Section 7.4.1.1, the following results show the impact that grouping restrictions targeted at confluences could have on peak discharge. Use of this technique is driven by efficiencies in installations required by stakeholders rather than any risk of confluences contributing to flood peak.

Table of restrictions						
Reach ID	ID 37	ID 53	ID 63	ID 195	ID 204	ID 216
Restriction applied	$1m^3s^{-1}$	$1.5m^3s^{-1}$	$2m^3s^{-1}$	$1.5m^3s^{-1}$	$5.5m^3s^{-1}$	$5m^3s^{-1}$
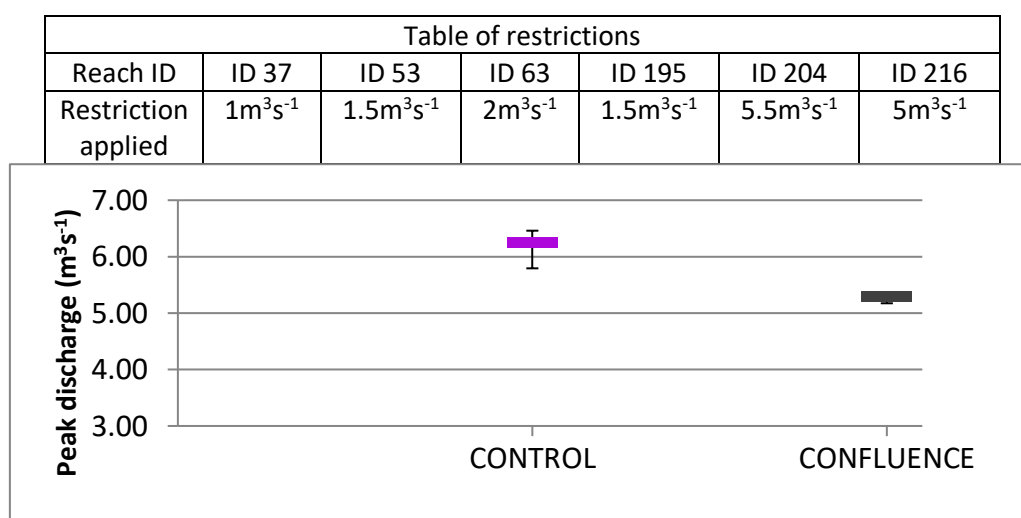
***Figure 7.13* Graph showing results of confluence-driven flow restrictions targeted according to table of restrictions above.**

This simulation reduced mean peak discharge to $5.29m^3s^{-1}$, a $0.95m^3s^{-1}$ reduction, with a variation from the mean of $0.17m^3s^{-1}$ between the 10th and 90th percentile. It used six barriers and produced an average reduction per barrier of $0.16m^3s^{-1}$. The result of this grouped simulation is not as effective as each individual restriction from Section 7.4.1.1 added together. This could be because simulations are along the same channel and, therefore, upstream restrictions reduce the flow that reaches downstream barriers. This action, however, reduces the flow rate to downstream barriers, which reduces pressure and also reduces the attenuation requirement of each flow restriction.

It is not recommended that barriers are sited on the confluences themselves as the combined channel width would probably exceed 5m. Furthermore, interaction of the two channels would create turbulence, increasing stress on a barrier and the likelihood of failure. Therefore, barriers

should be sited just downstream of these features where turbulence is lower and the channel narrows.

7.4.2 Unused area-driven flow restrictions

Another method would be to target interventions at locations where there is no productive land use, minimising the impact on farmers and landowners. Figure 7.14 shows the proximity of simulations to unused areas.
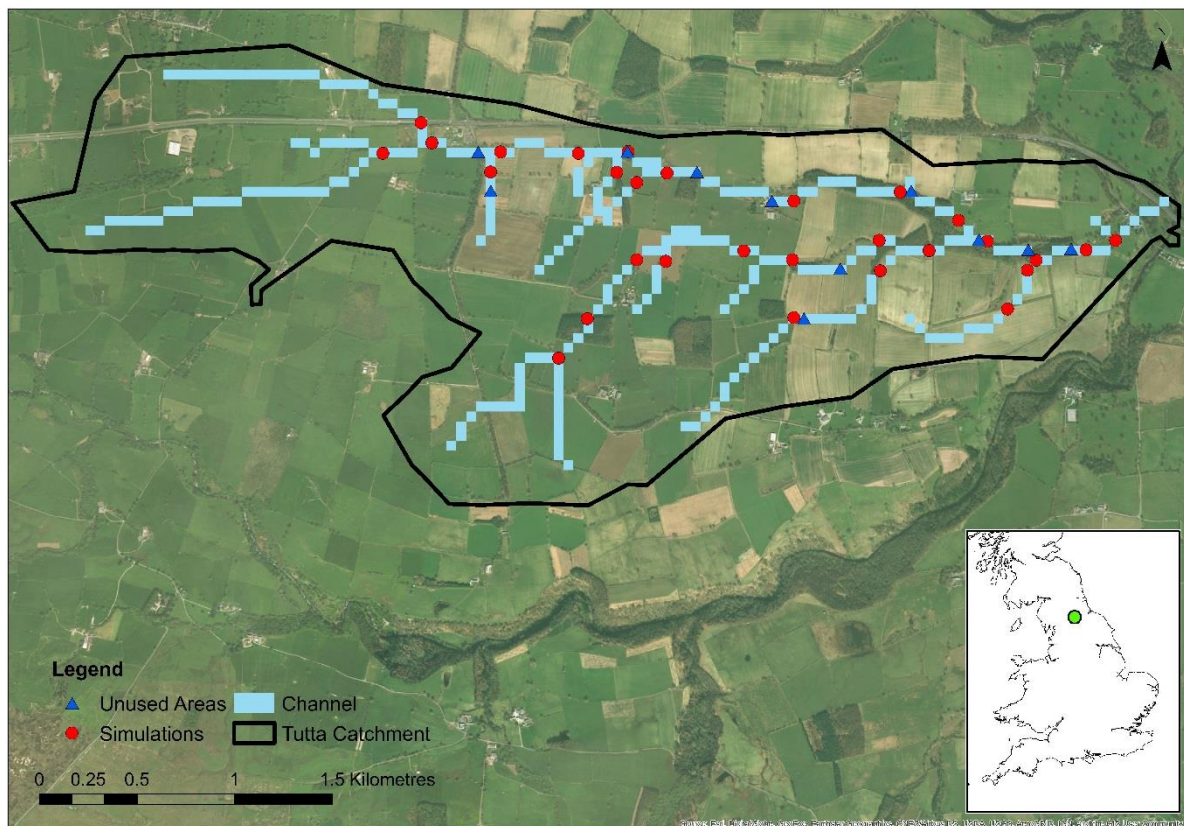
Figure 7.14 **Map showing location of unused area-driven flow restrictions and the simulations chosen for review across the catchment.**

7.4.2.1 Individual unused area-driven flow restrictions

The following graphs show the results from flow restrictions simulated near unused areas. These simulations are to ascertain whether or not installing flow restrictions in unused areas could deliver peak flow reductions.

Table 7.8 **Results of optimum unused area-driven flow restrictions**

Table of restrictions						
Reach ID	ID 53	ID 63	ID 118	ID130	ID 175	ID216
Restriction applied	$1.5m^3s^{-1}$	$2m^3s^{-1}$	$2.5m^3s^{-1}$	$2.5m^3s^{-1}$	$1m^3s^{-1}$	$5.5m^3s^{-1}$
Reduction in peak flow (m^3s^{-1})	5.90	5.81	5.60	5.83	5.75	6.02

These simulations all show a measurable reduction in peak flow because of the insertion of flow restrictions. As discussed, these simulations are not driven by a risk of unused areas generating or contributing to peak discharge, but have been undertaken to ascertain the potential effectiveness of targeting unused areas for the insertion of flow restrictions in the Tutta Beck catchment.

7.4.2.2 Grouped unused area-driven flow restrictions

Looking at the simulations in Section 7.4.2.1, the following results show the impact that grouping flow restrictions targeted at unused areas could have on simulated mean peak discharge.

Table of restrictions						
Reach ID	ID 53	ID 63	ID 118	ID130	ID 175	ID216
Restriction applied	$1.5m^3s^{-1}$	$2m^3s^{-1}$	$2.5m^3s^{-1}$	$2.5m^3s^{-1}$	$1m^3s^{-1}$	$5.5m^3s^{-1}$
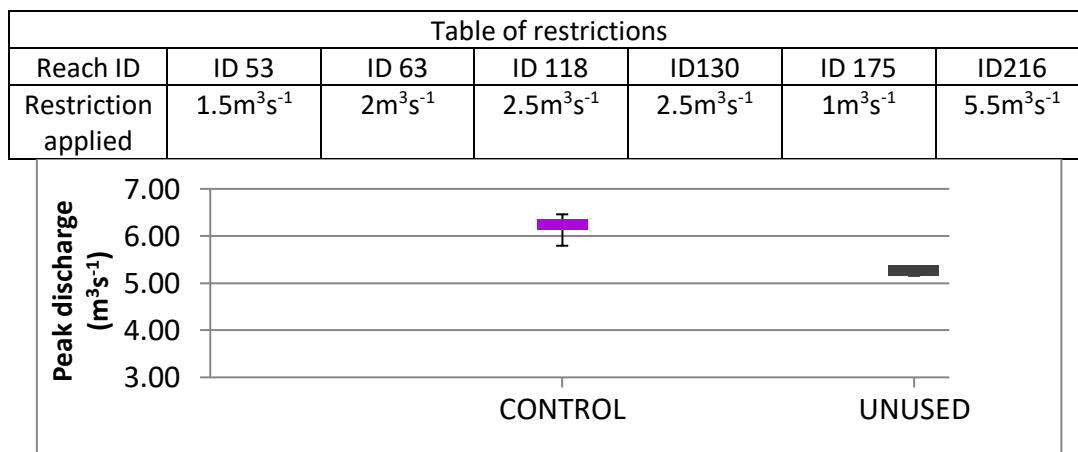
Figure 7.15 **Graph showing results of unused area-driven flow restrictions according to table of restrictions above.**

This simulation reduced mean peak discharge to $5.26m^3s^{-1}$, a $0.99m^3s^{-1}$ reduction, with a variation from the mean of $0.13m^3s^{-1}$ between the 10th and 90th percentile, suggesting high confidence in its potential effectiveness. It used six barriers and produced an average reduction per barrier of $0.17m^3s^{-1}$. The result of this grouped simulation is not as effective as each individual restriction from Section 7.4.2.1 added together. This could be because simulations are along the same channel and, therefore, upstream restrictions reduce the flow that reaches downstream barriers. This action, however, reduces the flow rate to downstream barriers, which reduces pressure and also reduces

the attenuation requirement of each flow restriction. An additional benefit is that this unused

storage potential may provide capacity to store exceedance volumes or account for uncertainties.

7.4.3   Bespoke grouped simulations

From stakeholder engagement and fieldwork there were several areas and theories discussed with

regard to the approach for targeting simulations. This section investigates those discussions.

7.4.3.1   Reducing the number of overlapping restrictions

All the above grouped simulations show that the sum of each restriction simulated in isolation is not

as great as when all restrictions are used as part of a grouped simulation. However, there are

benefits to this approach, such as reduced pressure on individual barriers and the potential for

downstream barriers to mitigate the potential surge effect from an upstream failure. The ultimate

effect is reduced effectiveness of individual barriers. Therefore, this section targets flow restrictions

at reducing the number of overlapping restrictions, for example, siting restrictions downstream of

other restrictions.

Table of restrictions						
Reach ID	ID 37	ID 63	ID 153	ID 195	ID 204	ID 208
Restriction applied	$1.5m^3s^{-1}$	$2m^3s^{-1}$	$3m^3s^{-1}$	$1.5m^3s^{-1}$	$5.5m^3s^{-1}$	$0.5m^3s^{-1}$
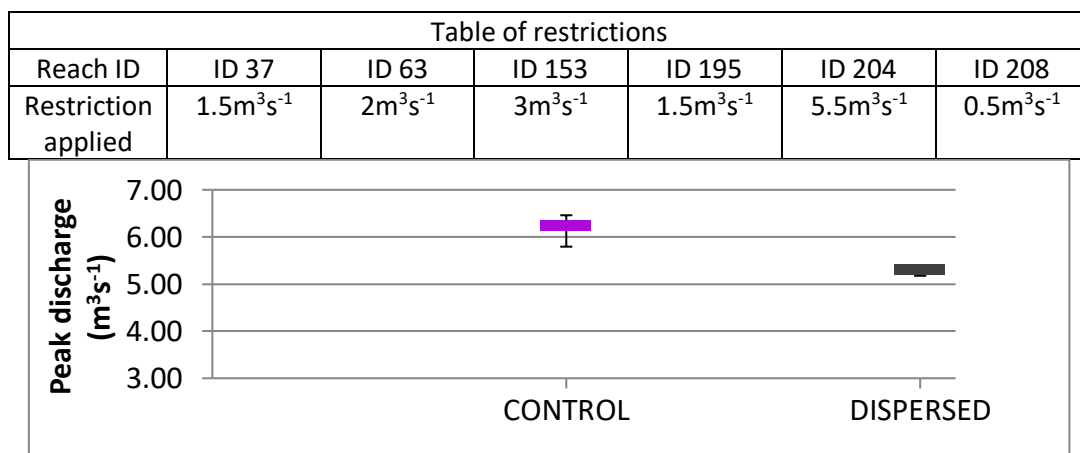
***Figure 7.16* Graph showing results of flow restrictions targeted at reducing the number of overlapping restrictions according to table of restrictions above.**

This simulation reduced mean peak discharge to $5.30m^3s^{-1}$, a $0.95m^3s^{-1}$ reduction, with a variation of

$0.17m^3s^{-1}$ from the mean between the 10th and 90th percentile. It used five barriers and produced

an average reduction per barrier of $0.19m^3s^{-1}$. The result of this grouped simulation yielded

measurable improvements to mean peak flow, and it does appear measurably more effective than

many other grouped simulations. This would, perhaps, be more significant in a large catchment with a systematic sampling regime. However, in a small catchment such as Tutta Beck, this approach does not have the number of channels to assess the supposed effectiveness.

7.4.3.2   Floodplain-driven flow restrictions

In many schemes in which flow restrictions are applied the floodplain is targeted. This is because it is a large area that can provide attenuation and resistivity to flow. Furthermore, promoting flooding out of bank during peak conditions is seem as reinstating natural processes.

Table of restrictions							
Reach ID	ID 118	ID 175	ID 182	ID 195	ID 204	ID 216	ID 228
Restriction applied	$2.5m^3s^{-1}$	$1m^3s^{-1}$	$5.5m^3s^{-1}$	$1.5m^3s^{-1}$	$5.5m^3s^{-1}$	$5.5m^3s^{-1}$	$0.25m^3s^{-1}$
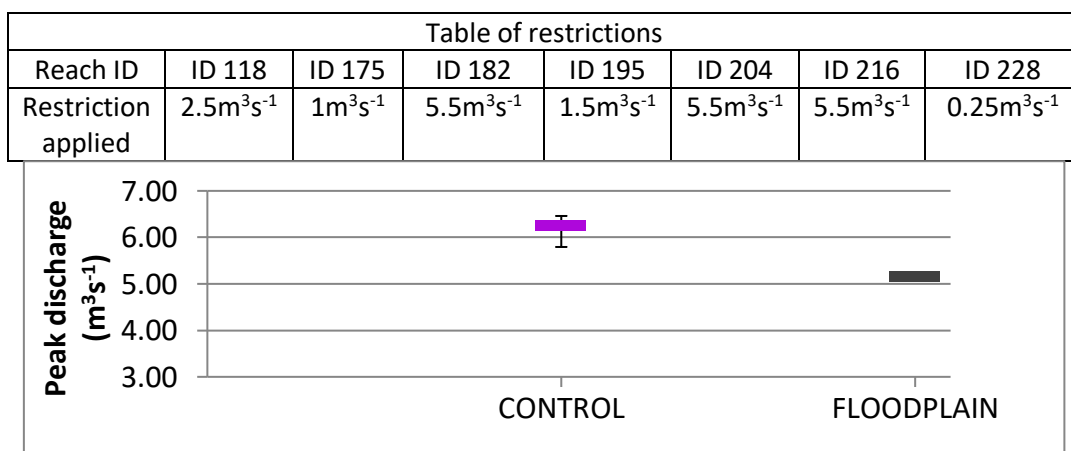
Figure 7.17 **Graph showing results of floodplain-driven flow restrictions targeted according to table of restrictions above.**

This simulation reduced mean peak discharge to $5.15m^3s^{-1}$, a $1.10m^3s^{-1}$ reduction, with a variation from the mean of $0.10m^3s^{-1}$ between the 10th and 90th percentile. It yielded the joint highest reduction in mean peak discharge; however, it used seven barriers with an average reduction of $0.16m^3s^{-1}$ per barrier. Furthermore, the lower catchment location of these restrictions requires them to be built with size and strength in mind so that they will hold greater volumes of water during flood conditions. This method does not target areas of the catchment with a propensity to cause flooding, but an area that has a higher storage potential than other locations. Restricting flow in this area would promote out-of-bank events, this would reconnect the watercourse with its floodplain.

7.4.3.3   Disconnecting the upper catchment from peak flows

Observations during site visits show a hydrograph rapidly responding to peak flows, potentially driven by the combination of the hydrophobic upper catchment and extensive drainage network. Therefore, simulations in this section aim to counteract the impact of drainage in the upper catchment with smaller interventions. The effect would be disconnecting the upper catchment from flood peak. Figure 7.18 shows the results of simulations.

Table of restrictions									
Reach ID	ID 10	ID 27	ID 44	ID 72	ID 74	ID 86	ID 209	ID 228	ID 249	ID 250
Restriction applied (m^3s^{-1})	0.25	0.5	0.25	0.25	0.25	0.25	0.25	0.25	0.5	0.25
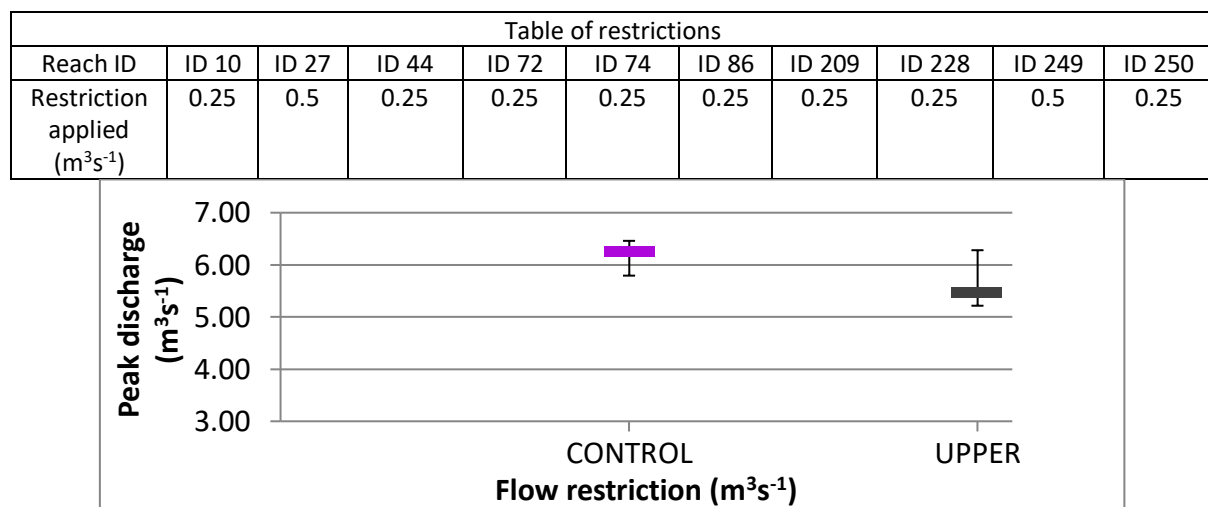
Figure 7.18 **Graph showing results of flow restrictions targeted at disconnecting the upper catchment from peak flows according to table of restrictions above.**

This simulation reduced mean peak discharge to $5.46m^3s^{-1}$, a $0.79m^3s^{-1}$ reduction, with variation of $1.06m^3s^{-1}$ from the mean between the 10th and 90th percentile, suggesting low confidence in the results. It used 10 barriers and produced an average reduction per barrier of $0.08m^3s^{-1}$. However, these features would not need to be as large or engineered due to lower discharge in this area of the catchment.

The concept of this mitigation is to disconnect and desynchronise the hydrographs from the upper and lower catchments. Delaying the upper catchment allows the peak discharge from the lower catchment to pass unhindered before the upper catchment reaches the downstream receptor. This works primarily on hydrograph timing rather than the volume of any restrictions. The error bars for this simulation display a different trend to other simulations: the positive error bar is larger, suggesting it is more likely that deviation from the mean will result in higher discharges.

7.5 SCIMAP-Flood-driven flow restrictions

Targeting flow restrictions using risk mapping software such as SCIMAP-Flood can enable all conditions linked to rapid runoff and peak flows to be considered simultaneously, unlike in sections 7.2 and 7.3, which investigated these mechanisms in isolation. Using Figure 7.19 it is possible to target LWD at areas displaying high flood risk. Many of the simulations are suitable for representing these areas.
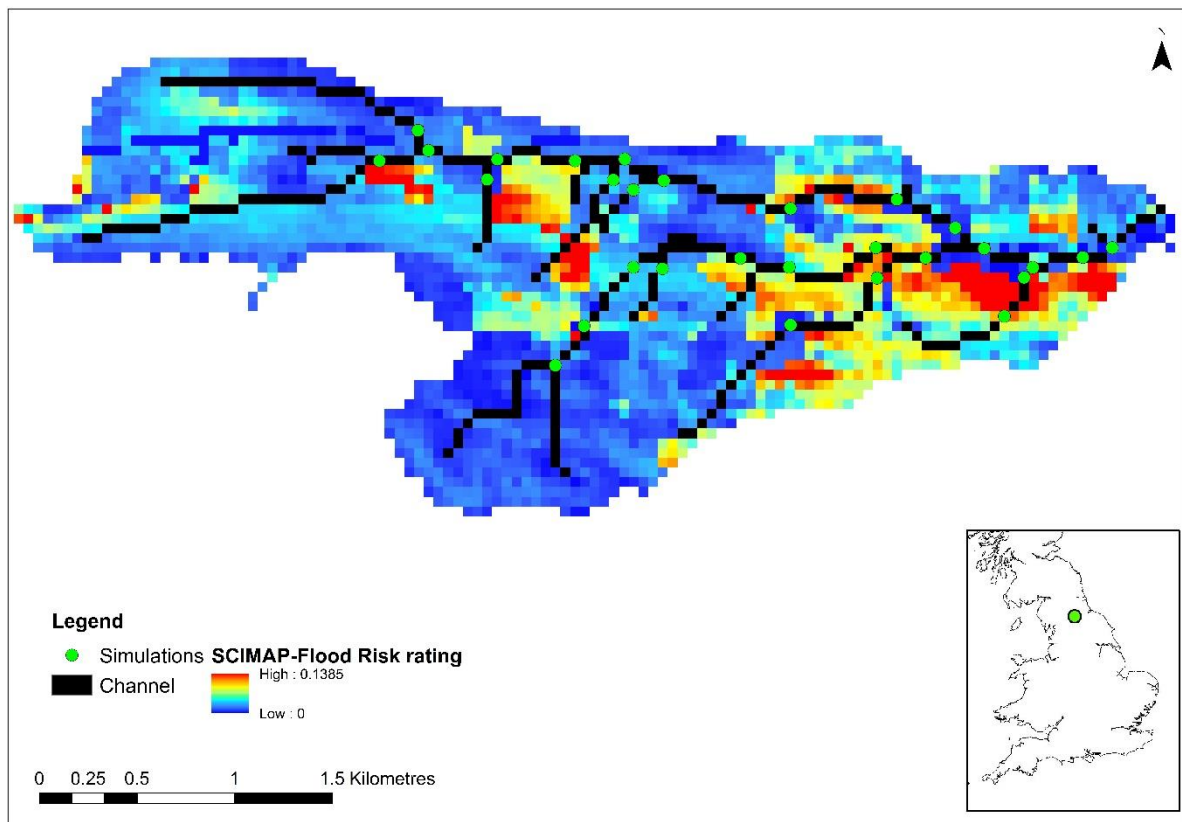
Figure 7.19 **Map of SCIMAP-Flood risk for the Tutta Beck catchment showing flow restriction simulations.**

7.5.1 Individual SCIMAP-Flood-driven flow restrictions

Of the simulations displayed in Figure 7.19, several lie in high-risk areas; these simulations will be reviewed to assess the potential for targeting flow restrictions at watercourses using SCIMAP-Flood.

***Table 7.9* Results of optimum SCIMAP-Flood-driven flow restrictions**

Table of restrictions						
Reach ID	ID 63	ID 118	ID 175	ID 182	ID 195	ID 204
Restriction applied	$2m^3s^{-1}$	$2.5m^3s^{-1}$	$1m^3s^{-1}$	$5.5m^3s^{-1}$	$1.5m^3s^{-1}$	$5.5m^3s^{-1}$
Reduction in peak flow (m^3s^{-1})	5.81	5.81	5.75	5.69	5.64	5.82

The simulations in Table 7.9 all show a measurable reduction in peak flow with flow restrictions inserted. Simulations show that targeting interventions at watercourses in areas of high risk may be effective in mitigating peak flows. Using SCIMAP-Flood to target restrictions appears effective, suggesting that the ability to consider multiple risk drivers, such as topography, land cover and proximity to channel, is beneficial. To conclusively prove effectiveness a larger sample and blind testing would be required. However, SCIMAP-Flood uses similar processes to a qualitative field assessment.

7.5.2 Grouped SCIMAP-Flood-driven flow restrictions

Looking at the simulations in Section 7.5.1, the following results show the impact that grouping restrictions targeted at SCIMAP-Flood high-risk areas could have on peak discharge.

Table of restrictions						
Reach ID	ID 63	ID 118	ID 175	ID 182	ID 195	ID 204
Restriction applied	$2m^3s^{-1}$	$2.5m^3s^{-1}$	$1m^3s^{-1}$	$5.5m^3s^{-1}$	$1.5m^3s^{-1}$	$5.5m^3s^{-1}$
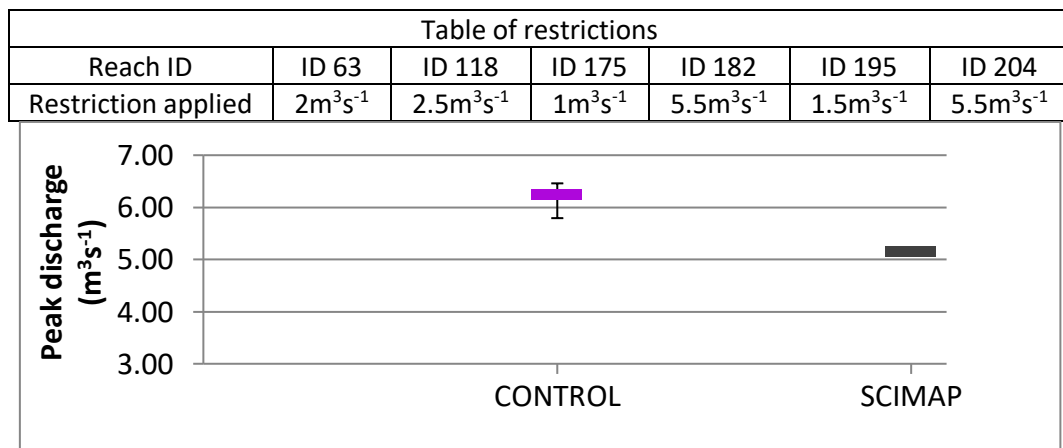
***Figure 7.20* Graph showing results of SCIMAP-Flood-driven flow restrictions according to table of restrictions above.**

This simulation reduced mean peak discharge to $5.15m^3s^{-1}$, a $1.10m^3s^{-1}$ reduction, with a variation from the mean of $0.11m^3s^{-1}$ between the 10th and 90th percentile, suggesting high confidence in the result. It yielded the joint highest reduction in mean peak discharge and used six barriers, which produced an average reduction per barrier of $0.18m^3s^{-1}$. The cumulative impact of all barriers from

Section 7.5.1 is not as much as each individual barrier. Potentially, this is because of upstream

restrictions reducing the impact of barriers downstream. This may be beneficial in that it reduces

pressure on barriers and provides storage potential in exceedance events.

7.5.3 Summary of SCIMAP-Flood risk mapping approach

All results in Section 7.5.1 yielded reductions in peak mean discharge through the application of flow

restrictions, suggesting that this approach does enable efficient targeting of interventions. This was

supported by the grouped scenario that reduced simulated mean peak discharge by $1.1m^3s^{-1}$, the

reduction rate per barrier being the fourth highest for any grouped simulation at $0.18m^3s^{-1}$.

7.6   Summary of flow restrictions

This section investigated the suitability of using LWD to reduce peak discharge in the Tutta Beck

catchment as well as the effectiveness of techniques to target interventions. Initially, individual

reaches were targeted to select the most effective restriction to apply in each location. Grouped

simulations were then developed to replicate common uses of LWD. The use of a single intervention

would require greater storage volumes to be effective in reducing flood risk. Not only would this

require more detailed design, it would not meet the design brief of replicating natural catchment

processes. From this work, the group simulations displayed in Figure 7.21 are the most suitable

choice for use in designing the FAS.

All grouped simulations reduced peak flows and could provide flood mitigation. The greatest

reductions were those targeted using SCIMAP-Flood and floodplain mitigation, which reduced mean

peak discharge to $5.15m^3s^{-1}$ and used six and seven barriers, respectively. SCIMAP-Flood offered an

effective reduction per restriction of $0.18m^3s^{-1}$; effectiveness is to be expected given consideration

of the multiple catchment processes that contribute to flood risk. The ability to consider multiple

flood risk drivers throughout the catchment simultaneously is valuable to flood risk managers and is

the process they aim to consider during qualitative assessments. SCIMAP-Flood can offer this

process to users without bias or individual interpretation, making it suitable for targeting investigations, surveys and hydrological modelling.

A limitation of SCIMAP-Flood is that it identifies rapid runoff connecting to a watercourse. Furthermore, there are limitations with regard to the likelihood that this runoff will contribute to peak flows and flood risk. To validate this, flood risk managers should review sub-catchment hydrograph timing to identify whether or not runoff contributes to peak flows. The inclusion of catchment sequencing will provide greater information on spatially distributed responses to rainfall, which could also be of value to water quality and other intervention scenarios.

7.7   Recommendations

Flow restrictions are best applied within a grouped scenario in which multiple features are used throughout the catchment. There are individual locations in the catchment that could be suitable for the use of single barriers: simulations in Section 7.4.3.2 at reach IDs 182, 204 and 216 all represent areas where a large single barrier could be applied. These areas would, however, be better suited to the installation of a more engineered structure similar to a flood storage reservoir. This structure may need to be located in the floodplain area downstream of the woodland and have a significant maintenance and management regime. This structure, although potentially feasible for the scheme, would not meet stakeholder aims of delivering a minimally intrusive scheme with multiple benefits.

The results of group simulations show that SCIMAP-Flood simulations (Section 7.5) offer the joint largest reduction at $5.15m^3s^{-1}$ and it is recommended that the locations in this simulation are used to form part of the FAS. Other significant reductions are stakeholder-driven simulations of unused areas (Section 7.4.2) and confluences (Section 7.4.1). These locations are also worth further investigation, particularly because of the higher degree of stakeholder acceptability. It would be worth consulting stakeholders with regard to the outputs from these model runs to assess their willingness to accept them, and in relation to potential costs, including any compensation payments.

A final area worth considering is the upper catchment. Although the measures recommended would not be as effective here, the low cost of design and insertion may mean that this area could be included in the other grouped scenarios. The use of these interventions may not be deemed suitable when using a risk-based approach common with NFM schemes in which pressure is not on the interventions to show 'benefits', but is brought to bear on an assessment of whether 'on balance' they would likely have a positive effect.

Peak Q	Control	Hillslope gradient	Channel gradient	All topographic drivers	Arable	Improved grassland	Both agricultural classes	SCIMAP-Flood	Confluences	Unused	Floodplain	Dispersed	Upper catchment
	6.25	5.63	5.42	5.43	5.64	5.91	5.47	5.15	5.29	5.26	5.15	5.30	5.46
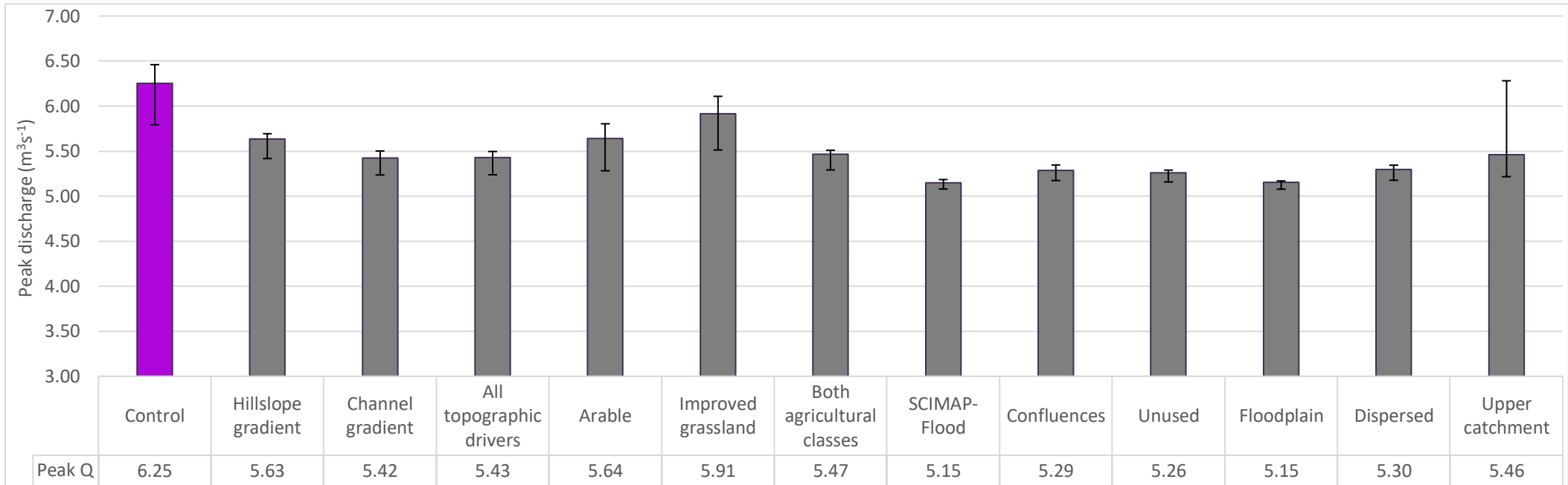
	Hillslope gradient	Channel gradient	Topography combined	Arable land	Pastoral land	Both agri. land covers	SCIMAP-Flood	Confluences	Unused	Floodplain	Minimal overlap	Upper catchment
No. flow restrictions	3	7	8	2	3	6	6	6	6	7	5	10
Reduction per barrier (m^3s^{-1})	0.21	0.12	0.10	0.31	0.11	0.13	0.18	0.16	0.17	0.16	0.19	0.08

Figure 7.21 **Graph showing results of all grouped simulations performed throughout the Tutta Beck catchment.**

Chapter 8   Combined Simulations

8.1   Introduction

This chapter presents the results of combining scenarios from land cover (Chapter 5), attenuation (Chapter 6) and flow restriction (Chapter 7). Stakeholders stated that attenuation and flow restriction were of primary interest to the investigation so combined scenarios will target these first before incorporating land cover change.

8.2   Combined attenuation and flow restriction scenarios

Flow restriction and attenuation simulations are combined in Table 8.1 to ascertain the potential effectiveness of utilising multiple mitigation techniques. All attenuation simulations use the 50cm-deep attenuation structures. Land take for attenuation is not total depression storage but includes land raising to provide a downslope bund required to create the attenuation feature. The combined flow restriction and catchment attenuation simulations are displayed in Table 8.1 and the simulation results displayed in Figure 8.1 and Table 8.2.

Table 8.1 **Scenarios for each combined simulation displayed in Figure 8.1**

		Attenuation simulations		
		SCIMAP-Flood simulation	Southern plateau	South-east catchment
Flow restriction simulations	SCIMAP-Flood simulation	Sc_1	Sc_4	Sc_7
	Floodplain simulation	Sc_2	Sc_5	Sc_8
	Unused area simulation	Sc_3	Sc_6	Sc_9
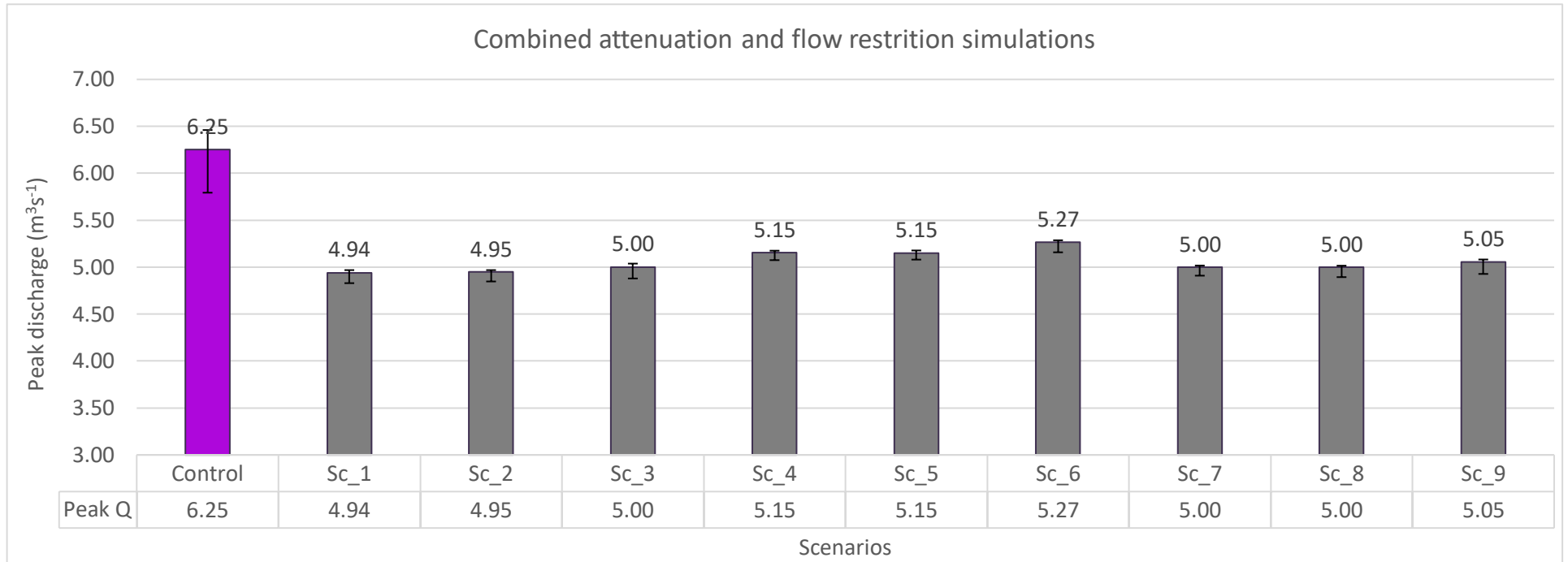
Figure 8.1 **Graph of results of combined flow restriction and attenuation simulations.**

Table 8.2 **Results of combined flow restriction and attenuation simulations**

Combined discharge scenarios	Control	Sc_1	Sc_2	Sc_3	Sc_4	Sc_5	Sc_6	Sc_7	Sc_8	Sc_9
Peak discharge 90th percentile (m^3s^{-1})	6.46	4.97	4.97	5.04	5.18	5.18	5.29	5.02	5.02	5.08
Upper peak discharge range (m^3s^{-1})	0.21	0.03	0.02	0.04	0.02	0.03	0.02	0.02	0.02	0.03
Mean peak discharge (m^3s^{-1})	6.25	4.94	4.95	5.00	5.15	5.15	5.27	5.00	5.00	5.05
Lower peak discharge range (m^3s^{-1})	0.46	0.11	0.10	0.12	0.08	0.07	0.11	0.09	0.10	0.13
Peak discharge 10th percentile (m^3s^{-1})	5.79	4.83	4.85	4.88	5.07	5.08	5.16	4.91	4.89	4.93
Sum of discharges 90th percentile (m^3)	4903.71	4650.03	4658.42	4650.74	4840.06	4850.77	4849.25	4702.88	4713.54	4708.37
Sum of discharges mean (m^3)	4467.41	4168.20	4206.66	4195.04	4350.97	4355.46	4362.27	4225.70	4246.79	4242.64
Sum of discharges 10th percentile (m^3)	3001.97	2772.56	2797.90	2781.48	2913.08	2912.68	2917.66	2821.91	2819.63	2812.03

Of the SCIMAP-Flood-targeted attenuation and flow restrictions scenarios, Sc_1 in Table 8.2 and

Figure 8.1 offered the greatest reduction, reducing simulated mean peak discharge to $4.94m^3s^{-1}$, a

reduction of $1.31m^3s^{-1}$ (20.96%). This simulation adjusted 14.5ha, equivalent to 2.05% of the

catchment, and used five flow restrictions of which only one is downstream of the Grahams Gill–

Tutta Beck confluence and may require a larger engineered restriction. Stakeholder discussions

identified this area as suitable for interventions. This simulation used the largest land take, which

means it could be costly to implement, even with design optimisation. Sc_2 and Sc_3 used the same

SCIMAP-Flood-driven attenuation simulations as Sc_1. Sc_2 targeted flow restrictions at the

floodplain and Sc_3 targeted flow restrictions at unused areas of the catchment. Sc_2 reduced

simulated mean peak discharge to $4.95m^3s^{-1}$, a $1.3m^3s^{-1}$ (20.8%) reduction. Sc_3 reduced simulated

mean peak discharge to $5m^3s^{-1}$, a $1.25m^3s^{-1}$ (20%) reduction. Figure 8.1 shows that attenuation

driven by SCIMAP-Flood used in Sc_1, Sc_2 and Sc_3 offered the greatest response to interventions

than any other simulation.

The results of the combined simulations in Figure 8.1 show that Sc_4, Sc_5 and Sc_6, which are all

targeting attenuation at the southern plateau, offer the lowest mean peak flow reduction under all

flow restriction simulations. This simulation adjusted 1.5ha, equivalent to 0.21% of the catchment

and this is the smallest attenuation area used in any of the three simulations. However, only a single

stakeholder identified the area so this could cause difficulties with regard to reaching an agreement

on installation. The 90th and 10th percentile error bars for these simulations are small, between

$0.1–0.13m^3s^{-1}$, suggesting good correlation within the various runs. The smaller reduction in

discharge and the unknown resistance to measures suggest the most suitable way to use this

simulation would be as a supplementary measure to complement another mitigation proposal.

To avoid the large land take and in accordance with stakeholder wishes, the SCIMAP-Flood

attenuation simulation was reduced to target the south-east area of the catchment. This simulation

adjusted 9.25ha, equivalent to 1.31% of the catchment. The greatest reductions for this attenuation

driver were through Sc_7 and Sc_8. Sc_7 targeted flow restrictions through SCIMAP-Flood and Sc_8 targeted restrictions at the floodplain. Both scenarios reduced simulated mean peak discharge to $5.00m^3s^{-1}$, a $1.25m^3s^{-1}$ (20%) reduction. The simulation using SCIMAP-Flood is the most effective because it uses five barriers, only one of which is downstream of the Grahams Gill–Tutta Beck confluence and could require a larger engineered structure. The area is arable land with steep hillslopes. A site visit on 5 December 2016 found evidence of high runoff with significant sediment loading, thereby justifying SCIMAP and SCIMAP-Flood analysis. The land take for these simulations is 9.25ha and the land currently has an agricultural stewardship agreement leaving an unplanted strip at field boundaries. Adjusting this land to form a vegetated swale, DoF or similar could have benefits with regard to water quality as well as providing the opportunity to improve drainage function for farmers.

8.3   Incorporating land cover change

As mentioned in Section 8.1, stakeholders suggested land use change for flood mitigation would be difficult to incorporate within a FAS. However, there are mechanisms through which land cover change could be included. Therefore, in this section we consider the most suitable options to implement on site in conjunction with outputs from Section 8.2. The simulations investigated are: a 25m deciduous woodland watercourse buffer; a CSF scenario; and changing arable land to deciduous woodland. The results of these simulations are displayed as follows:

- combined scenarios (nine) from Section 8.2 with a 25m deciduous woodland buffer, as shown in Figure 8.2 and Table 8.3;

- combined scenarios (nine) from Section 8.2 using a CSF approach, as shown in Figure 8.3 and Table 8.4; and

- combined scenarios (nine) from Section 8.2 introducing a change of arable land to deciduous woodland, as shown in Figure 8.3 and Table 8.5.
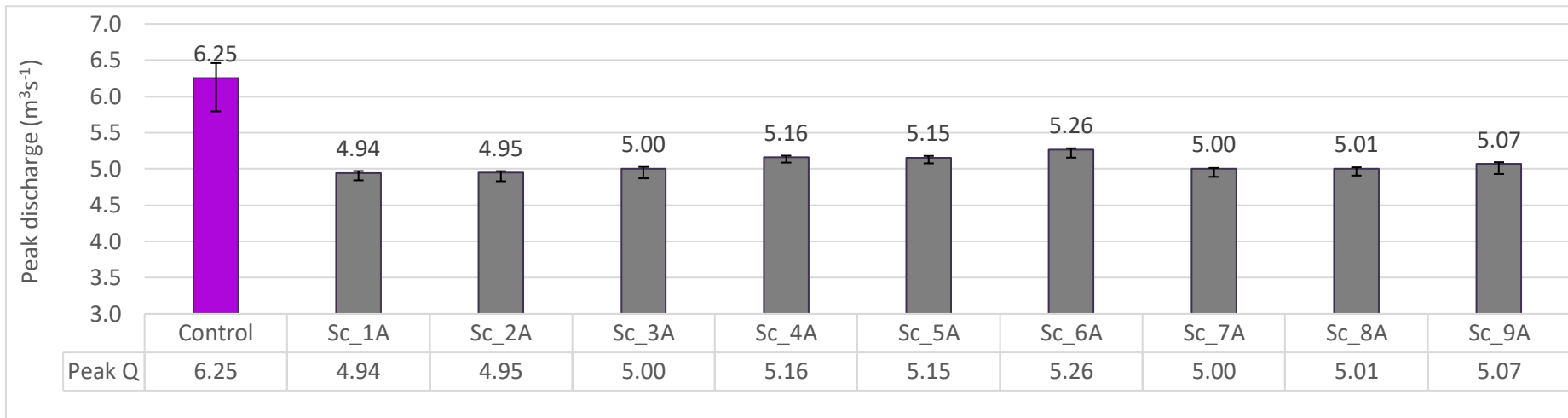
(a)

Figure 8.2 Graph of results of the nine combined flow restriction and attenuation scenarios amalgamated with the 25m deciduous woodland buffer.

Table 8.3 Results of the nine combined flow restriction and attenuation simulations amalgamated with the 25m deciduous woodland buffer

25m Deciduous woodland buffer										
Combined discharge scenarios	Control	Sc_1A	Sc_2A	Sc_3A	Sc_4A	Sc_5A	Sc_6A	Sc_7A	Sc_8A	Sc_9A
Peak discharge 90th percentile (m^3s^{-1})	6.46	4.96	4.96	5.03	5.17	5.17	5.29	5.01	5.01	5.08
Upper peak discharge range (m^3s^{-1})	0.21	0.07	0.07	0.11	0.07	0.08	0.11	0.06	0.06	0.09
Mean peak discharge (m^3s^{-1})	6.25	4.89	4.88	4.92	5.11	5.10	5.18	4.95	4.95	4.98
Lower peak discharge range (m^3s^{-1})	0.46	0.28	0.26	0.29	0.28	0.27	0.35	0.28	0.29	0.31
Peak discharge 10th percentile (m^3s^{-1})	5.79	4.61	4.63	4.63	4.83	4.82	4.83	4.67	4.66	4.68
Sum of discharges 90th percentile (m^3)	4903.71	4638.91	4650.52	4638.70	4815.28	4828.20	4819.26	4686.27	4695.76	4687.16
Sum of discharges mean (m^3)	4467.41	4149.54	4154.41	4149.98	4316.03	4327.26	4316.31	4169.89	4192.75	4184.08
Sum of discharges 10th percentile (m^3)	3001.97	2563.04	2578.18	2559.36	2659.81	2670.20	2663.45	2595.83	2601.31	2592.66

(b)

Figure 8.3 Graph showing results of the nine combined flow restriction and attenuation scenarios amalgamated with CSF.

Table 8.4 **Results of the nine combined flow restriction and attenuation simulations amalgamated with CSF**

	CSF woodland									
Combined discharge scenarios	Control	Sc_1B	Sc_2B	Sc_3B	Sc_4B	Sc_5B	Sc_6B	Sc_7B	Sc_8B	Sc_9B
Peak discharge 90th percentile (m^3s^{-1})	6.46	4.97	4.95	5.03	5.17	5.16	5.28	5.01	5.02	5.09
Upper peak discharge range (m^3s^{-1})	0.21	0.02	0.02	0.04	0.01	0.01	0.03	0.03	0.02	0.02
Mean peak discharge (m^3s^{-1})	6.25	4.95	4.94	4.99	5.16	5.15	5.25	4.99	4.99	5.06
Lower peak discharge range (m^3s^{-1})	0.46	0.11	0.10	0.10	0.08	0.07	0.10	0.08	0.10	0.13
Peak discharge 10th percentile (m^3s^{-1})	5.79	4.84	4.84	4.89	5.08	5.07	5.16	4.91	4.89	4.94
Sum of discharges 90th percentile (m^3)	4903.71	4665.12	4678.52	4679.11	4851.78	4866.77	4857.76	4710.61	4732.01	4721.50
Sum of discharges mean (m^3)	4467.41	4172.85	4200.66	4174.81	4354.70	4369.79	4366.05	4230.83	4264.57	4242.99
Sum of discharges 10th percentile (m^3)	3001.97	2791.46	2772.66	2778.03	2918.52	2927.68	2924.28	2819.61	2826.39	2831.60
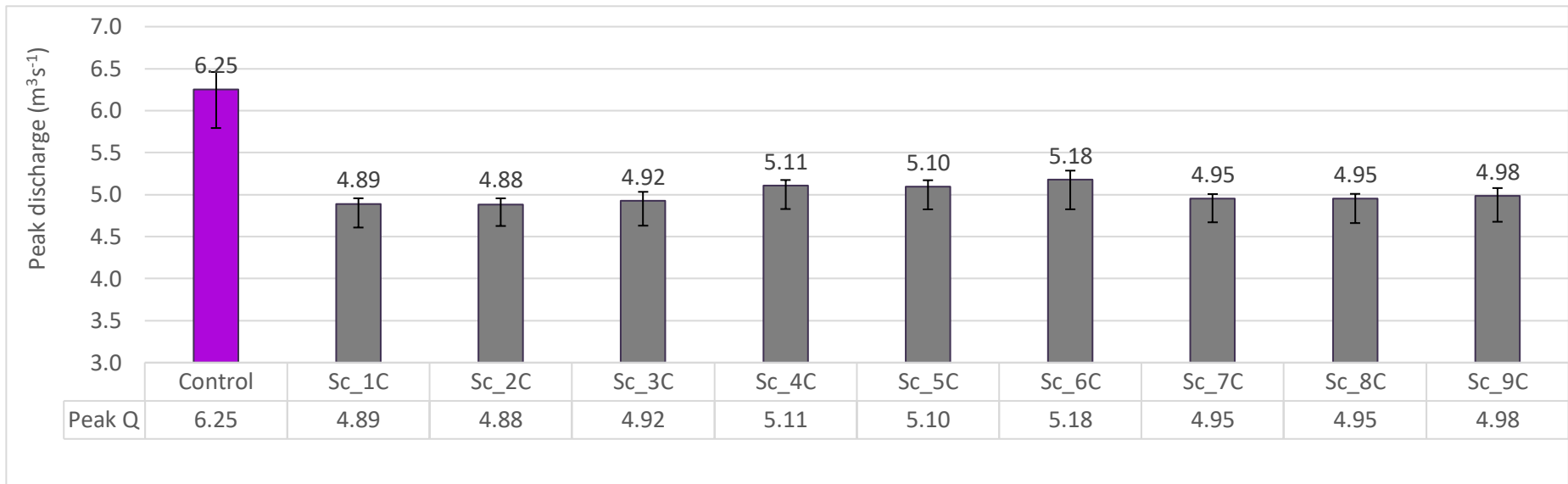
(c)

Figure 8.4 Graph showing results of the nine combined flow restriction and attenuation scenarios amalgamated with the change of arable land to deciduous woodland.

Table 8.5 Results of the nine combined flow restriction and attenuation simulations amalgamated with the change of arable land to deciduous woodland

Arable to BLW										
Combined discharge scenarios	Control	Sc_1C	Sc_2C	Sc_3C	Sc_4C	Sc_5C	Sc_6C	Sc_7C	Sc_8C	Sc_9C
Peak discharge 90th percentile (m^3s^{-1})	6.46	4.96	4.96	5.03	5.17	5.17	5.29	5.01	5.01	5.08
Upper peak discharge range (m^3s^{-1})	0.21	0.07	0.07	0.11	0.07	0.08	0.11	0.06	0.06	0.09
Mean peak discharge (m^3s^{-1})	6.25	4.89	4.88	4.92	5.11	5.10	5.18	4.95	4.95	4.98
Lower peak discharge range (m^3s^{-1})	0.46	0.28	0.26	0.29	0.28	0.27	0.35	0.28	0.29	0.31
Peak discharge 10th percentile (m^3s^{-1})	5.79	4.61	4.63	4.63	4.83	4.82	4.83	4.67	4.66	4.68
Sum of discharges 90th percentile (m^3)	4903.71	4638.91	4650.52	4638.70	4815.28	4828.20	4819.26	4686.27	4695.76	4687.16
Sum of discharges mean (m^3)	4467.41	4149.54	4154.41	4149.98	4316.03	4327.26	4316.31	4169.89	4192.75	4184.08
Sum of discharges 10th percentile (m^3)	3001.97	2563.04	2578.18	2559.36	2659.81	2670.20	2663.45	2595.83	2601.31	2592.66

Looking at Figure 8.2, Figure 8.3 and Figure 8.4 as well as Table 8.3,Table 8.4 and Table 8.5, it can be seen that land cover change combined with attenuation and flow restriction scenarios can reduce simulated mean peak discharge to a greater degree than outputs from the scenarios described in Section 8.2 alone. Of the three scenarios, both CSF and the 25m deciduous buffer offered little variation to simulated mean peak discharge, with only ±0.01m^3s^{-1} change, which could be from variations within the model itself.

Changing land cover throughout all arable areas provided a measurable benefit with regard to the attenuation and flow restriction simulations, with reductions varying from 0.04m^3s^{-1} to 0.09m^3s^{-1}. The greatest reduction was through Sc_2C with SCIMAP-Flood-driven attenuation and floodplain-driven flow restrictions, reducing simulated mean peak discharge to 4.88m^3s^{-1}, a 1.37m^3s^{-1} (21.92%) reduction. This is a 0.07m^3s^{-1} greater reduction than Sc_2 in Section 8.2. Sc_1C offered the next greatest reduction in simulated mean peak discharge to 4.89m^3s^{-1}, 0.01m^3s^{-1}, less than the reduction offered through Sc_2C in Table 8.5 and 0.05m^3s^{-1} greater than Sc_1 in Table 8.28.2. In Sc_3C the reduction through the addition of arable to deciduous woodland scenario resulted in a simulated mean peak discharge of 4.92m^3s^{-1}, a 1.33m^3s^{-1} (21.28%) reduction. This is a 0.08m^3s^{-1} greater reduction than Sc_3 in Table 8.2.

An interesting trend to note is that the simulated reductions in Sc_3C, Sc_6C and Sc_9C scenarios, targeting flow restrictions to unused areas, offered a greater rate of change than other simulation criteria in Figure 8.2 and Table 8.3 as well as Figure 8.3 and Table 8.4. The greatest change between simulations in Section 8.3 (Figure 8.3 and Table 8.4) compared to Section 8.2 (Figure 8.1 and Table 8.2) was Sc_6C, with a reduction of 0.09m^3s^{-1}. This resulted in a simulated mean peak discharge of 5.18m^3s^{-1}, a reduction of 1.07m^3s^{-1} (17.12%) from the control simulations.

As could be expected from Chapter 5, incorporating land use change for flood mitigation offers limited benefits, particularly when considering the large land take required. However, discharge

reduction is not the sole benefit from land use change. Other benefits include: enhancing ecosystems and natural capital; reducing diffuse pollution; and WFD improvements.

8.4   Conclusion and recommendations

The primary focus of this research is to reduce flood risk by reducing mean peak discharge. Therefore, the primary recommendation must be the simulation that offers the greatest reduction. Sc_2C in Table 8.5 and Figure 8.4 offers the greatest reduction using a combination of arable to deciduous woodland land use change, SCIMAP-Flood-driven attenuation and flow restrictions. There are difficulties associated with including land cover/management change, most notably with performing, maintaining and securing this change in perpetuity.

The limited effectiveness brought about by using land cover interventions means there is little justification to progress with this and it may be more suitable to use the physical interventions simulated in Section 8.2. From these simulations, the primary recommendation would be Sc_1, a simulation using SCIMAP-Flood to drive attenuation and flow restrictions. Sc_2 also has a similar reduction using SCIMAP-Flood to drive attenuation and flow restrictions targeted at the floodplain. By targeting the floodplain at the downstream end of the catchment it is likely there will be a requirement for more detailed design with the resulting associated costs. The small variance means that the most suitable scenario for development in the catchment would be decided on through discussion and eventual agreement with the landowners and the flood management authority. Other simulations, such as Sc3, Sc_7 and Sc_9, could be used to develop the final FAS for use in the catchment and some design improvements could be used within these scenarios to reduce discharge further.

The combined simulations displayed in this chapter offer the most promising results for developing a FAS. Adopting different techniques and approaches means multiple benefits can be delivered while still meeting the core aim of flood mitigation. The approach using in-channel flow restrictions, such as LWD, does not have an impact on low flows and, therefore, does not create an ecological barrier.

Attenuation simulations would not interact with the watercourse and, therefore, would not alter freshwater ecology. However, they facilitate the dropping out of suspended sediment and agricultural pollutants, thus improving water quality. The land cover change simulations, if adopted, could improve interception of runoff, thereby improving water quality. They would also provide new habitats as well as benefits to soil structure. It is the additional benefits available through the development of these simulations that strengthens the case for their insertion as opposed to traditional approaches.

Chapter 9   Discussion and Conclusions

9.1   Introduction

The primary aim of this thesis was **to investigate, using hydrological modelling tools, the potential for reducing flood risk using NFM, SuDS and land management techniques and interventions**. The achievement of this aim is assessed against the repeated research questions displayed in Section 9.2.

This research was undertaken with the aim of aligning it with the FCERM industry, using the SCIMAP-Flood risk mapping and CRUM3 hydrological modelling approaches. The results are presented in chapters 5–8 using the methodology employed in Chapter 4.

9.2   Research aims and objectives

The following research aims and objectives drove this research and are reintroduced here to identify whether they have been addressed, require further work or have not been answered.

9.2.1   To develop a framework for RMAs for investigating the feasibility of delivering a FAS using NFM

This research is based on two complementary approaches: (1) rapid connectivity and risk mapping assessment (SCIMAP-Flood); and (2) detailed, physically based, fully spatially distributed simulation of water flow within the catchment (CRUM3). These methods combine to provide a powerful toolkit to effectively target mitigation measures within the catchment and to predict the potential reduction in the flood peak from interventions.

Using SCIMAP-Flood helps RMAs consider complex catchment processes and begin investigations into catchment-scale risk at the earliest stages of project appraisal. The benefits of this process in understanding the catchment cannot easily be captured but rely on the ability to interpret results. This research did not seek to capture these benefits but they are worth noting.

The research demonstrates the relative effectiveness of the SCIMAP-Flood approach in identifying areas likely to contribute to flood risk. If a fully distributed catchment model, such as CRUM3, exists, it provides an opportunity for focusing investigations and targeting simulations. However, for FRMs, particularly at large catchment scales, these models are commonly too expensive; therefore,

traditional models are used. In such instances, the risk mapping has the potential to be used for targeting how a catchment will be included in modelling. 'NFM-suitable' sub-catchments may have a full 2D-1D linked model to simulate interventions, whereas others use a simple inflow hydrograph to represent catchments without NFM interventions.

The research identified the need for an intermediary tool that could 'find' suitable NFM locations from catchment characteristics. This would be useful specifically for those interventions such as flow restriction on attenuation. However, interventions such as flood storage and channel interventions require locations that would be compatible with their construction, not just areas of high risk. This research suggests that to adopt the approach of targeting specific catchments for detailed modelling would require at least an intermediary step to assess storage potential and consider relative risk. For land cover change, using SCIMAP-Flood is still potentially a suitable approach as these interventions do not require compatible locations.

9.2.2   To support the development of a FAS for the Tutta Beck catchment that minimises impact on agriculture

The options identified in chapters 5–8 all result in simulated reductions in peak flows (identified as the primary source of risk in the catchment) as well as having minimal impact on agricultural land, or would have, by optimising design. Discussions with the landowner and tenant farmer suggested these options could feasibly be used in the future should their design be sympathetic to agriculture. The tenant farmer was particularly interested in the opportunity for reducing sediment losses and discussed ways in which he could incorporate the recapture of sediment or the prevention of the start of erosion on site independently of the FAS.

Ultimately, the outputs of this research are not sufficiently detailed to deliver a FAS. However, the concept can be used to inform a detailed appraisal and design. Furthermore, the current level of detail could be sufficient to submit an outline business case that could justify funding for this body of

work. Although not conclusively demonstrated, this research does provide the means of progressing the FAS.

9.2.3 Determine the potential impact rural land management interventions could have on flood risk and if this hazard reduction is sufficient to protect receptors

This study identified the potential for land management to change simulated mean peak discharge. The changes were small; therefore, it is anticipated that they would not be deemed effective because they would not be sufficient to deliver the required benefits. There was insufficient data available to conclusively determine this either way. As such, further investigation is required with regard to specific flood events and return periods. This research question could only determine a potential for change, not capture whether or not this hazard reduction is sufficient to protect receptors.

What *can* be inferred from the data in this study is that rural land management changes do offer a reduction in peak flow. However, flood risk in any catchment is dictated by conditions at the receptor as much as by those in the upper catchment. To this end, when applying a catchment-scale assessment of flood risk, we need to ensure that the receptor is not overlooked. Given the likelihood that flooding in this location would occur in the Tutta Beck catchment due to flow driving water out of bank before the capacity of the culvert bridge is reached, then riparian issues may be more significant for investigation than upstream interventions.

9.2.4 Assess whether or not SCIMAP-Flood is a suitable targeting mechanism for FRM interventions over other approaches

In reviewing the various 'simple' options with regard to targeting NFM interventions, such as slope and land cover, it can be identified that an approach that assesses multiple factors contributing to runoff risk is, perhaps unsurprisingly, more effective.

Discussions with farmers and organisations involved in flood risk and farm management enabled effective conceptualisation of the risk mapping approach. Essentially, the tool performs the same

task as an individual would do when looking at a site to consider risk of runoff. However, it does so consistently without interpretation bias and simultaneously across the catchment for each individual input. This is not feasible for the individual and, therefore, SCIMAP-Flood provides a useful tool when combined with local and/or technical knowledge to inform the appraisal of intervention options. This technique does not, however, consider point source inputs unless further analysis is built into the model outputs

9.3   Challenges to implementation

The three key challenges to the implementation of NFM measures are part of FRM:

1. delivering benefits and evidence sufficient to satisfy funding regulations;

2. delivering a suite of measures that could be implemented within the available budget; and,

3. delivering a suite of measures that could be acceptable to landowners and farmers.

To deliver the evidence base for funding, the CRUM3 hydrological model has been used to simulate mitigation measures, the results of which have been discussed. Recommendations for detailed design have been outlined in this chapter. After completing the GLUE analysis results and weighting of existing land cover, a simulation of the existing catchment hydrological regime was created to establish a control or baseline. Using techniques from Chapter 2, the simulations in chapters 5, 6, 7 and 8 show that CRUM3 can predict the impact that flood mitigation measures can have on high flows and allow the effectiveness of the different mitigation schemes to be appraised.

Delivering a suite of measures acceptable to stakeholders has involved a review of literature, stakeholder engagement and the involvement of other partners such as Northumberland County Council. The conflict between local authorities and landowners is common in agricultural catchments with significant controversy surrounding flood mitigation through catchment management and NFM. Recently, the Thorneythwaite Farm project in the Borrowdale Valley has met with significant opposition from local farmers who see it as a top-down approach endangering their livelihoods and

cultural heritage. The farm was purchased by the National Trust for a rewilding and NFM programme (Case, 2016; Cohen, 2016; McKenna, 2016; Parveen, 2016). The local authority–landowner conflict is more pronounced when an authority seeks to perform works on third-party land. Discussions at the Northumberland CSF Steering Group (2016a, 2016b, 2016c) and with National Farmers Union representatives (ARUP, 2015) stated that catchment management should be about persuading farmers to buy into these initiatives and reward them for adopting good practice. To mitigate these challenges, it was important to ensure that catchment interventions were proportional to the benefits achievable and that spatial targeting was adopted to mitigate the need to modify large swathes of the catchment.

There are challenges to working on any farmland. At Tutta Beck these have been mitigated by early engagement with stakeholders and identifying areas that could be removed from agricultural function or be temporarily inundated. An additional option could be subcontracting the farmer to perform works, thereby mitigating the possibility of damage compensation payments.

9.4   Simulation evaluations

This section evaluates the effectiveness of simulations performed and considers combining techniques to produce a comprehensive catchment management plan.

9.4.1   Land cover change simulations

Land management is a commonly cited contributor to flood risk associated with agricultural catchments (DCLG, 2016) due to the loss of a natural catchment's ability to store and slow the flow of water (SEPA, 2015). This process can be observed in the Tutta Beck catchment where the majority of the land is managed for agriculture. Agricultural catchments, including Tutta Beck, are noted as being susceptible to recurrent rainfall events that saturate the catchment, generating rapid runoff resulting in flood hazard (Alstead, 2013). Chapter 5 presented the results of simulations targeting land cover change to mitigate flood risk. These simulations also served as a proxy for land management changes that demonstrate similar impacts to land cover change. Land cover change

modifies infiltration, porosity and surface roughness, which can all be replicated in land management through techniques such as soil aeration, cover crops and agroforestry.

Blanketing the catchment in woodland provided the greatest peak flow reduction of $5.67m^3s^{-1}$, a 9% reduction, and represents the largest potential alteration through land cover change. This is not believed to be a sufficient reduction to deliver benefits, and the costs associated with land take mean land cover change could not be considered as an independent mitigation measure. Therefore, land cover will only be considered as a contributory technique alongside another measure. This is common across other NFM schemes in which the planting of woodland is targeted at parcels of land and is seen as an improvement without a determined target of change. Stakeholder engagement reinforced this view and it was suggested that land cover change simulations could be used in the future to align with other funding sources. Suitable methods could be floodplain planting, hedgerow enhancement, buffer strips and other initiatives that could be supported long term by alternative funding sources such as CSF.

The challenges with land cover change centred primarily on what constitutes an effective change in peak discharge and what is efficient considering loss of earnings and cost of planting. In reviewing Chapter 5, the most suitable simulated changes would be those that were proxies for improving land management, such as the simulation changing all arable land to deciduous woodland. This option reduced simulated mean peak discharge to $5.84m^3s^{-1}$. It targeted the highest risk land use, could attract agri-environment funding and, because of its necessarily blanket adoption, any new equipment required to perform interventions could be used across a wide area.

The use of CSF woodland for flood alleviation resulted in an efficient reduction in flood risk (reduction in discharge per hectare). This proposal reduced simulated mean peak discharge to $6.07m^3s^{-1}$. This intervention is the most efficient land use change intervention with a reduction of $0.0058m^3s^{-1}ha^{-1}$. However, the reduction is not great enough to suggest it is sufficient for flood risk purposes. Further spatial targeting of interventions could be performed by looking at combinations

of targeting strategies. This approach, however, would be best driven by the funding source and through engagement between the funding provider, the RMA and the landowner.

9.4.2   Attenuation simulations

Attenuation is a common strategy for flood mitigation and can be either online or offline, with or without positive drainage. CRUM3 cannot simulate online storage due to limitations of the model. Similarly, CRUM3 cannot simulate positive drainage reconnecting to the channel. As such, attenuation simulations can only be conceptualised by modifying the topographic dataset for the 2D part of the model. CRUM3 operates at 50m resolution, which means that modifying a single cell takes up 2,500m^2. Combined with a downslope embankment this requires even greater land take, which would be unfeasible for the catchment. It is anticipated that design optimisation could, at minimum, deliver equivalent reductions for less land take than simulated in CRUM3. Therefore, simulations could only be used to conceptualise the scenario with further modelling required to design structures.

Scenario 8 is another simulation that could yield measurable benefits, although it is not in a place identified as a risk area through any of the mapping scenarios. This simulation was inserted due to the proximity of two channels, the plateau-like conditions across this area of the catchment and a request by stakeholders. For a 1m-deep attenuation structure, simulated mean peak discharge was reduced to 6.07m^{3}s^{-1}, which is significant considering the small land take for this structure compared to others. This area could be worth further investigation and if the RMA could combine this with an online storage structure and flow restriction a more significant impact could be delivered.

The grouped simulations in Chapter 6 show that topography- and SCIMAP-Flood-driven simulations offer the greatest reductions in simulated mean peak discharge. Using this information, a newly created grouped attenuation simulation targeting the south-east of the catchment was developed. This was not simulated in isolation but was used in the combined simulations in Chapter 8.

9.4.3   Flow restriction simulations

Of all the techniques available, flow restrictions offer the greatest reduction in simulated mean peak discharge and LWD is a common and popular technique in NFM schemes. Results of simulations show that almost all targeting mechanisms offer effective reductions in simulated mean peak discharge; however, some are more effective at reducing discharge than others. It is important when designing structures that the RMA considers potential volumes at structures and also the risk of failure. Barriers such as those used in Alwinton (Fraser *et al.,* 2016; Fraser & Reaney, 2017; Fraser *et al.*, 2017) could be suitable for use in the upper catchment of Tutta Beck. Where the contributing area is larger, more engineered restrictions may be required due to the greater volumes of water and the higher risk of hazard associated with a failure.

The SCIMAP-Flood-driven simulations reduced simulated mean peak discharge to $5.15m^3s^{-1}$, a 17.6% reduction using six flow restrictions. These simulations are all located in areas of the catchment that stakeholders identified as acceptable for interventions and could be temporarily inundated. The combined drivers of SCIMAP-Flood demonstrate that the targeting of flow restrictions using this technique is effective for the Tutta Beck catchment.

Targeting flow restrictions at the floodplain area also produced an effective reduction in discharge to $5.15m^3s^{-1}$, a 17.6% reduction, although this simulation used a combination of seven flow restrictions. All but one of these were in areas identified through stakeholder engagement as suitable for the use of temporary inundation and would, therefore, have lower costs than simulations elsewhere in the catchment. Three of the restrictions are located downstream of the Grahams Gill–Tutta Beck confluence and could require larger engineered barriers at a greater cost.

Given the potential for high costs associated with constructing restrictions at the downstream end of the catchment a further simulation removing the restriction at reach ID 182 (bottom of floodplain) was performed. The simulation reduced mean peak discharge to $5.16m^3s^{-1}$, a 17.4% reduction, suggesting this restriction had minimum impact on overall reduction as part of the combined

simulation. This prompts a question as to whether or not other combined simulations can be made more effective by optimising the design, or whether or not the exceedance storage potential is of greater interest. With reduced confidence in the design of NFM structures, retaining these exceedance structures is a more suitable approach to adopt.

A final simulation worth further investigation would be to target flow restrictions at unused areas of the catchment. This simulated a reduction in discharge of $5.26m^3s^{-1}$, a reduction of 15.84% using six flow restrictions. All restrictions were targeted at unused areas or those that stakeholders identified as suitable for temporary inundation and, therefore, would have lower costs than other simulations. Only one of these simulations is located downstream of the Grahams Gill–Tutta Beck confluence and this could require a larger, engineered barrier.

Chapter 7 demonstrates that flow restrictions offered the greatest potential for flood mitigation in the Tutta Beck catchment and measures are typically lower in cost than many others. These simulations do require compensatory storage to be effective and the design needs to consider the volumes required to be effective. Failure to do so could mean the structures cease to operate effectively, causing overtopping or potential failure.

9.4.4 Combined scenarios

By combining the simulations in chapters 5, 6 and 7 it is possible to target different contributors to flood risk and there is the potential for this approach to be more effective than individual techniques even when used multiple times. Combining techniques can also increase the exceedance potential to accommodate extreme weather events. In addition, it would reduce the likelihood of an asset failing by reducing attenuation volume. This may mean that in some schemes there is no need for a freeboard/uncertainty allowance to achieve the same factor of safety.

The recommendations and results in Chapter 8 show the greatest reduction is by combining all three techniques into one simulation. The specific scenarios offering the greatest reduction were:

- land cover change, targeted by replacing arable land with deciduous woodland;

- attenuation, targeted by using SCIMAP-Flood; and

- flow restrictions, targeted by using SCIMAP-Flood.

Delivering this land cover change would be difficult for several reasons: the cost of using the land would be high; purchasing sufficient trees to stock the area would be expensive; and, finally, mobilising resources to plant trees would be prohibitively expensive. Therefore, as previously stated, this simulation is proxy for changes in land management. There would still be difficulty in funding such initiatives through a FAS, particularly as this may require machine purchases or simply cost farmers more in terms of money and time. It may be more suitable for these mitigation measures to form part of a catchment scheme funded outside of the FAS. This could be delivered using agri-environment funding, such as the NFM options within Countryside Stewardship agreements (NFU, 2016a; Natural England, n.d.), or a facilitation fund such as that available within the River Coquet catchment (Gov.UK, 2016; NFU, 2016b). Therefore, land cover change simulations will be closed for combined simulations with a recommendation that the RMA engages other stakeholders to discuss the feasibility of a wider agri-environment scheme for the area.

Removing land cover change from combined simulations produced significant reductions in itself, principally because other techniques appear more effective than land cover change. The greatest reduction was through SCIMAP-Flood-driven attenuation and SCIMAP-Flood-driven flow restrictions. Coincidentally, these simulations fall within areas identified by stakeholders as suitable locations for interventions. Attenuation could feasibly be constructed in the existing field margins retained as part of a pre-existing Countryside Stewardship agreement. The flow restrictions are in unused areas, in woodland or on the floodplain, all favourable locations for the land owner and which would have minimal impact on the site's agricultural function.

Significant reductions are also available through SCIMAP-Flood-driven attenuation combined with floodplain-driven flow restrictions. There are two negatives from this simulation:

- first, there would be some reduction in agricultural land; and

- second, floodplain storage at the bottom of the catchment would probably need a more engineered structure to store flood waters safely.

During the winter of 2015–2016 the field where floodplain storage is simulation, was not in productive use and there was some floodplain inundation. Therefore, it may be feasible to only have to exclude the field from its agricultural function periodically. Stakeholder engagement did identify this area and approach as feasible; however, there was concern over the requirement for an engineered structure to manage volumes and the impact this could have on agriculture, and with regard to potential inspection and maintenance costs. Furthermore, these structures could have a significant visual impact on the area, raising similar objections to previous proposals (Alstead, 2013), particularly in proximity to the ancient monument.

9.5 Alternatives to catchment management

Although this research prioritises catchment management and a sustainable approach it must be acknowledged that there are alternatives to this approach. Although not investigated as part of this research they should be discussed for future purposes.

One such example is to review the suitability of the catchment outlet. As mentioned in Chapter 3, the bridge was widened to carry increased trans-Pennine traffic in the 1950s prior to the construction of the A66 trunk road as it exists today, making the bridge widening redundant. The bridge is now used only for access to the cottages and private land and has recently been restricted back down to a single lane. This original bridge widening resulted in a restriction to the eastern bridge span displayed in Figure 9.1, which means the 3.2m-wide culvert bridge does not operate at capacity. This low flow promotes the build up of the type of debris displayed. One mitigation option could, therefore, be the removal of this now redundant extension and abutment; the extension is an independent structure so costs for this option would be minimal.

Figure 9.1 **Image showing the confined entry into the eastern span because of the bridge widening (author, 15 November 2016).**

Further capacity is lost through utilities, which have concrete surrounds and have been built into the

spans, as can be seen in Figure 9.2. Methods of mitigation could be to divert the connection

elsewhere or under the road, thereby discharging downstream of the bridge.

(a)

(b)

Figure 9.2 Image showing the two bridge spans (a) eastern span; (b) western span (author, 31 January 2016).

Another option for this catchment outlet could be to perform works downstream of the culvert bridge, thereby re-establishing an archway through the listed structure and widening this section of the watercourse. Figure 9.3 shows the watercourse downstream of the culvert bridge (image taken looking east from bridge wall). As can be seen, the channel width is compromised by overgrown debris on the north bank and in higher events the bricked-up archway could provide an overflow for the watercourse during high flows. There is a challenge to developing this option in that an alteration to a listed structure would have to be permitted and there could be significant pressure to make the structure strong enough to convey flows. Since Figure 9.3 was taken there has been work carried out on the north bank in that the vegetation has been cut back; however, such maintenance

will be required at least annually. This is the responsibility of the landowner, so can go unchecked for

a long period of time and is often only noticed when it causes a problem, which could be too late.

Figure 9.3 **Image showing the watercourse downstream of Tutta Beck bridge looking east (author, 15 November 2016).**

These options are for this catchment alone and show that careful consideration during development

around watercourses is particularly important, because an improved hydrologically conscious design

could result in reduced flood risk in this location.

9.6   Implications of this research for other UK rural catchments

NFM is a growing option for RMAs across the UK, primarily due to rural catchments failing to meet

central funding criteria for larger schemes. The primary aim of this thesis was **to investigate, using**

hydrological modelling tools, the potential for reducing flood risk using NFM, SuDS and land

management techniques and interventions.

The framework for this research focused on providing a mechanism for delivery and, therefore,

involved consultation with RMAs and other parties. The key challenge for implementing any

landscape management scheme is stakeholder buy-in, because the funding regulations mean that if

any scheme is to go ahead it requires the willingness of landowners to participate. Talk of regulation

change is common, but difficult practically. Increasing the emphasis on flood risk in agri-environment schemes may help, as would better integration of RMAs in such plans. CSF does include flood risk but only for woodland planting. Not engaging local authorities could mean missed opportunities. Furthermore, there may be scope for local levy funding to be used as top-up funding for such initiatives if it could be demonstrated there would be benefits for flood risk.

Initially, during engagement with stakeholders, there was disagreement regarding the high-risk areas identified from SCIMAP-Flood risk mapping. However, site visits during the storms of 2015–2016 found many of the at-risk areas identified had evidence of high runoff and this showed that SCIMAP-Flood can help stakeholders learn about their land by enabling them to think from an unfamiliar perspective.

The research showed that scenarios identified as suitable for other catchments (Smith, 2012; Pearson, 2016) may not actually be appropriate for applying elsewhere. The Tutta Beck catchment is a small rural one, and land cover and land management changes resulted in limited benefits, which meant that large areas required modification. Flow restrictions yielded the most suitable management practice due to their limited impact on agricultural land and relative effectiveness with regard to reducing peak flows. Attenuation simulations offered flood mitigation benefits; however, it would be better to use these to complement flow restriction simulations or have their design optimised in a hydraulic modelling package.

9.6.1   Role of stakeholders

As discussed, stakeholder engagement was undertaken as part of this research, not with residents but predominantly with the Tees Rivers Trust, the land agent and Durham County Council. Engagement was carried out to establish the guidelines and scope for investigation rather than invite feedback and this information was then used to inform the simulation targeting. The results of engagement generated the following principles:

- minimise loss of agriculturally productive land;

- provide multiple benefits in water quality improvements where possible; and

- minimise the visual impact of intervention measures.

Engagement also yielded opportunities: stakeholders indicated areas where floodplain inundation would be acceptable and where existing ponds could be enlarged to deliver mitigation.

Procurement regulations with regard to FAS allow for payment to a landowner-approved contractor. The Alwinton FAS is an example of this (Green, 2016b; Fraser et al., 2017). The stakeholder is no longer a person to be engaged but an active partner; this represents a powerful change in perspective. In Alwinton, the tenant farmer constructed barriers to agreed standards and subsequently went on to publish articles with the NFM in which he praised the approach. Communication with the landowner, tenant farmer and the Tees Rivers Trust has identified that this would be the preferred solution for the Tutta Beck catchment. The benefits of this approach include the residents having a sense of ownership over these assets and monitoring them, even though responsibility would remain with the local authority.

9.7 Recommendations for the FAS

The primary aim of this thesis is **to investigate, using hydrological modelling tools, the potential for reducing flood risk using NFM, SuDS and land management techniques and interventions**, the methods for which were presented in Chapter 4.

The simulations performed using SCIMAP-Flood are assessed against targeting techniques driven by catchment characteristics, such as topography and land cover, as well as non-technical targeting mechanisms, for example, unused areas that have no agricultural function. The targeting demonstrated that targeting techniques driven by SCIMAP-Flood were commonly more effective, particularly given their ability to consider multiple drivers of flood risk and runoff. The results of these simulations are presented in chapters 5–8 and discussed in earlier sections of this chapter. The

recommendations from these simulations are presented in Appendix 2. There are three

recommended options for each intervention technique which are:

- land cover change targeted to watercourses using a buffer;

- land cover change of arable land to deciduous woodland;

- land cover change targeted at CSF;

- attenuation driven by land cover;

- attenuation driven by SCIMAP-Flood;

- attenuation targeted at solely the south-east of the catchment;

- LWD targeted at the floodplain;

- LWD targeted using SCIMAP-Flood; and

- LWD targeted at unused areas of the catchment.

The key techniques identified through hydrological modelling were LWD and attenuation; land cover

was not deemed effective for flood risk unless performed over large areas, for example, targeting

changes at all arable land. There is an opportunity to consider options for changes in land use

management in these areas; however, stakeholders felt this approach would be difficult to deliver

and could hold up a FAS.

The recommendations in Appendix 2 are indicative, should not be scaled and do require detailed

hydraulic modelling. However, these options should form the basis of further investigations

discussed in Section 9.8.

9.8   Recommendations for future research

Due to current time and access restraints there are potential areas for further research that could be

carried out to develop this project. Compaction and parameter sets were taken from calculations

performed for a basin area in the River Eden catchment. It would have been desirable for saturated

conductivity, soil porosity and dynamic layer depth values to have been captured through

observation/fieldwork. However, in-field variance for infiltration readings shows that categorising the catchment accurately could be difficult and inefficient.

The land cover dataset LCM2007 (Morton et al., 2011) is not always entirely accurate or able to be generalised. Land cover could be measured across the catchment by increasing the number of categories, particularly within the current category of arable land, to allow for the individual hydrological responses of each very specific land cover type. Furthermore, the seasonality of vegetation should be better considered. During the winter, most arable areas are left in various stages of management, including as stubble, ploughed or sown with overwinter crops. Again, this could be captured, with the detail of these changes incorporated within the modelling. Such investigation could lead to better management advice on what planting regime would better complement flood mitigation and reduce hydrological connectivity.

A significant investigation that could be undertaken is the impact of drainage from the A66 road on the hydrological regime of the catchment. Much of the A66 drainage connects with Tutta Beck. However, the timing of this would be difficult to accurately simulate using CRUM3 and would require drainage simulations and separate inflow hydrographs. Considerations with regard to this approach include: the conveyance rate of infrastructure discharging into Tutta Beck; outfall height and presence of flap valves; and the contributory area (subsurface drainage can drain across watersheds). An alternative to future works could be to agree a discharge rate with Highways England and retrofit SuDS solutions, thereby reducing discharge to the watercourse.

Spatial resolution is a significant limitation referred to throughout this research. CRUM3 currently operates at a 50m grid resolution, which means that the model can overlook some processes, such as overflow channels, that can have an impact on the hydrological regime. The 50m x 50m cell size failed to identify roads and many impervious surfaces, as well as hedgerows and land drainage systems both above and subsurface. Improving the resolution of data sources could significantly improve the results and could also improve the outputs from model simulations.

Temporal resolution was also a restriction. CRUM3 uses a long duration time series, which means that surface depressions can fill through small events. This means that filling, overflowing and discharge would not be representative of a positively drained attenuation area that would drain down between storms. Resolving these limitations would require a separate modelling study and perhaps the integration of a subsurface modelling package such as MicroDrainage or Flood Modeller that could also be incorporated with CRUM3.

Chapter 10   Conclusion

This study concludes that a physically based, spatially distributed hydrological model, notably CRUM3, can be used to model NFM at a catchment scale and quantify the impact that such mitigation may have on discharge. The CRUM3 hydrological model was used to assess the potential for scenarios, including spatially targeted land use change, attenuation through DEM manipulation and flow restrictions, to slow the propagation of water downstream.

Stakeholder engagement and industry advice were sought to help develop flood mitigation scenarios and provide advice with regard to the delivery of such schemes. Stakeholders for this project included the Tees Rivers Trust, Durham County Council, the landowner (Rokeby Estates) and tenant farmers. Engagement centred on a range of topics, most notably:

- acceptability to stakeholders and impact of interventions on the farming landscape;

- understanding the needs of the regulator to satisfy funding regulations for delivering the scheme;

- validating thoughts on and outputs from risk mapping with regard to catchment processes;

- long-term design considerations for the catchment.

Flow restriction simulations yielded the greatest reductions in simulated mean peak discharge and, given the relatively small watercourses, it is anticipated that features would be small and relatively cheap to install (in Alwinton approximate costs were £1,500 per timber barrier for materials and construction). Simulations using multiple barriers targeted using SCIMAP-Flood reduced simulated mean peak discharge by 17.76% with five restrictions; many NFM schemes target a 5–10% reduction.

Catchment attenuation would also be worth further investigation, particularly if design can be optimised using a SuDS approach of attenuation and positive drainage, which reduced the storage capacity required for a given event. Simulations targeted using topography and SCIMAP-Flood were the most effective, suggesting that, for this catchment, topography has greater influence on overland flow than land cover.

Simulations based on land use found large areas of the catchment required modification to deliver measurable benefits. Stakeholders confirmed there was no desire for such measures to form part of the FAS and it was likely that they would not receive funding anyway. Consequently, land cover change does not form part of FAS recommendations for this scheme.

The findings and methodology presented in this research could be applied to similar catchments dominated by overland flow to develop an effective flood mitigation solution. However, the techniques used in this research are only sufficient to make conceptual recommendations with regard to the interventions. Providing more detailed design guidance would require modelling of various design changes, including storage potential on the floodplain as well as positive drainage in attenuation structures.

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Appendices

Appendix 1.   The CRUM3 Hydrological Model

This appendix outlines the CRUM3 hydrological model and is a reproduction of that in Lane *et al.*,

(2009). The CRUM3 hydrological model is a fully spatially distributed physically based process base

model representing hydrological processes. The model processes displayed in the following sections

are representative of processes that could be observed and measures throughout the catchment.

Weather

To produce the data resolution required, CRUM3 uses a stochastic weather generator to produce

per-minute discharge predictions from a diurnal weather dataset using an approach by Mulligan

(1996) and interrogated in Lane et al. (2009) (Smith, 2012; Pearson, 2016). The generator uses

tipping bucket data to characterise storm and rainfall events and generates random storm events

through the day using a Monte Carlo model. Solar radiation is calculated using solar geometry in

relation to the latitude of the catchment and day of year. The weather model interpolates per-

second temperature from daily maximum and minimums using Equation 8.

Equation 8

$$T_{a(s)} = \frac{Sin(\frac{d_s + td + (15 * 60 * 60)}{4 * 60 * 60} + 1)}{2} * (t_{mac} - t_{min}) + t_{min}$$

$T_{a(s)}$ is the current air temperature,
d_s is the current second of the day,
td is the time between midday and the maximum temperature occurring,
t_{mac} is the daily maximum temperature,
t_{min} is the daily minimum temperature.

Point-scale hydrological processes

CRUM3 simulates the processes occurring in each area across the catchment and a conceptual

diagram is displayed in Figure 1 (Appendix 1). CRUM3 simulates rainfall interception by vegetation,

infiltration in soil, aquifer recharge and surface water storage, including generation of throughflow

and runoff (Lane et al., 2009; Smith, 2012; Pearson, 2016).
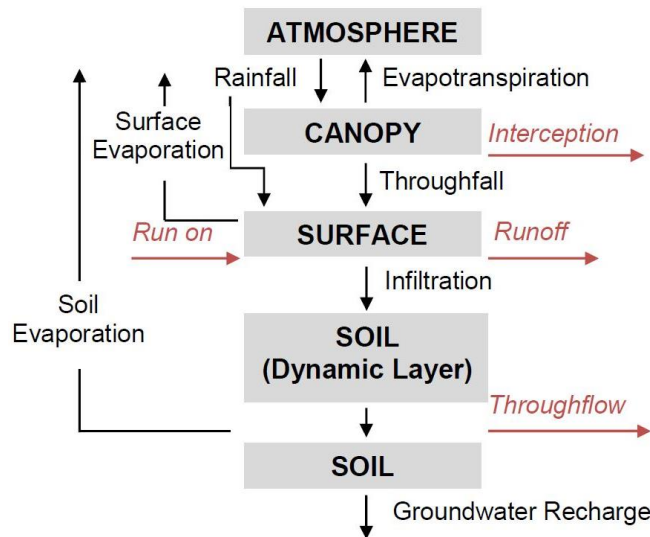
Figure 1 Appendix 1 **Conceptual diagram of CRUM3 hydrological processes (Smith, 2012).**

Rainfall interception is divided into direct throughfall and intercepted water, controlled by canopy

gap fraction. The intercepted volume then fills the canopy store, which is calculated from vegetation

type and biomass. This then overflows and the canopy store is emptied by means of evaporation.

CRUM3 can calculate evapotranspiration using both the Penman–Monteith equation (Penman,

1948; Monteith, 1965) and the Priestley–Taylor equations (Priestley & Taylor, 1972). The most

accurate is the Penman–Monteith method, which has detailed data requirements: temperature,

relative humidity, wind speed, solar radiation and vegetation characteristics (Dingman, 1994). Not all

this data is available for the Tutta Beck catchment and, therefore, the Priestly–Taylor method has

been selected. This is displayed in Equation 9.

$$PET_{PT} = \frac{\propto_{PT} \Delta(R_n - G)}{\Delta \gamma}$$

Equation 9

PET_{PT} is the potential daily evapotranspiration,
$\propto_{PT}$ is the Priestly–Taylor constant, which under normal conditions is 1.26,
Δ is the slope of the saturation vapour pressure temperature relationship,
R_n is the net radiation,
G is the soil heat flux,
γ is the psychometric constant.

Net radiation is determined from the energy arriving at the top of the atmosphere, the transmission

through the atmosphere to the surface and the amount reflected by the surface. The variation in the

amount of energy reaching the surface depends on depth of the atmosphere and local weather

conditions of which Dingman (1994) identified cloud cover as the most influential. CRUM3 uses

Equation 10 to calculate the reduction in energy on a cloud-free day.

Equation 10

$$R_{ES} = R_{TA} * 0.5$$

R_{ES} is the amount of solar radiation reaching the earth's surface,
R_{TA} is the amount of radition at the top of the atmosphere.

When days are determined to have cloud cover this is reduced by 50%. Cloudy days are determined

as all days of measured rainfall and a selection with no measured rainfall as computed using a Monte

Carlo model. Once at the surface, radiation can then be directly reflected or emitted as long-wave

radiation. This is determined by surface albedo and computed using Equation 11.

Equation 11

$$r_{sw} = R_{ES} * a$$

r_{sw} is the reflected short-wave radiation,
a is the surface albedo.

The amount of long-wave radiation emitted is determined by temperature and surface emissivity

and is computed by Equation 12.

Equation 12

$$r_{lw} = e_{ms} * (5.6695 * 10^{-8}) * (T_a + 273.15)^4$$

r_{lw} is the emitted long-wave radiation,
e_{ms} is the surface emissivity,
T_a is the air temperature.

Once reflected radiation has been removed, the remaining solar radiation reaching the surface is

used to drive evapotranspiration. Evapotranspiration occurs from several stores: vegetation,

transpiration, soil surface and in soil. The evapotranspiration rate from the canopy store and soil

surface occurs at the potential rate, which is determined by Scott (2000) using Equation 13.

Equation 13

$$t_p = PET_{PT} * (-0.21 + 0.7^{LAI})$$

t_p is the potential transpiration,
PET_{PT} is the potential evapotranspiration rate,
LAI is the leaf area index.

The actual transpiration rate is related to vegetation rooting depth and the availability of water in the dynamic layer and in the man soil store. The water retention characteristics of the soil limit the amount of water available for evaporation from the soil matrix using Equation 14.

Equation 14

$$e_\theta = PET_{PT}\theta$$

e_θ is the soil moisture-dependant evaporation rate,
PET_{PT} is the potential evapotranspiration rate from the Priestly–Taylor equation,
θ is the soil moisture content (m^3 water/m^3 pore space).

The processes of evapotranspiration are controlled by vegetation characteristics and, therefore, will be subject to significant changes as a result of the land cover change simulations in Chapter 5.

Detention and depression stores are determined from the surface gradient and roughness; depression store is water detained in surface troughs due to roughness and detention store is the water detained above the surface store. Depression store depth is calculated using Equation 15 from Kirkby et al. (2002).

Equation 15

$$\frac{dp}{a} = 0.11\exp\left(\frac{-0.02\beta}{a}\right)$$

dp is the surface depression storage capacity,
a is the surface roughness,
β is the slope gradient.

The a value can be related to the random roughness coefficient (Allmaras et al., 1966) using Equation 16.

Equation 16

$$RR = 0.657a$$

CRUM3 generates overland flow in three ways: (1) infiltration excess (Hortonian); (2) saturation driven; and (3) return overland flow (caused by topographic routing and overland flow overwhelming soil storage capacity causing overflow (Lane et al., 2009). Infiltration excess overland flow occurs when the rainfall rate is greater than infiltration capacity. Infiltration capacity is

calculated through a simplification of the Green and Ampt (1911) equation developed by Kirkby (1975, 1985), Equation 17.

Equation 17

$$i = a + \frac{b}{\theta}$$

i is the infiltration rate,
θ is the soil moisture,
a and b are coefficients.

Soil depth influences hydrological processes significantly and can be related to geomorphological form, as identified in Huggett and Cheesman (2002). Therefore, within CRUM3, catchment topography is categorised into ridges, slopes, channels and plains, and consistent properties are assigned within these areas, typically in the structure:

Channels > Plains > Ridges > Slopes

Groundwater recharge is determined from minimum hydraulic conductivity at the base of the soil profile and the hydraulic conductivity of the underlying bedrock (Lane et al., 2009)

Landscape processes

CRUM3 utilises spatial information in a raster grid structure, whereby each cell generates and receives water laterally by throughflow or as overland flow, which can be under laminar, transitional or turbulent conditions and is represented using the Darcy–Weisback equation (Abrahams et al., 1995, Baird, 1997), Equation 18.

Equation 18

$$v = \sqrt{\frac{8gRs}{ff}}$$

v is the velocity of overland flow,
g is the gravity constant,
s is the slope,
ff is the friction factor.

Overland flow routing in CRUM3 is calculated using the FD8 algorithm (Quinn et al., 1991), which allows water to flow from one cell into multiple neighbouring cells, unlike single-flow routing

methods such as D8. This detailed flow routing aids CRUM3 in representing both hydrological flow

dispersal and concentration. The flow allocated to each cell is determined on a slope-weighted basis

(Freeman, 1991; Quinn et al., 1991), Equation 19.

Equation 19

$$F_i = \frac{\beta_i^v}{\sum_{i-1}^{8} \beta_i^v}$$

β_i is the slope from central cell to neighbour i,
v is the flow concentration factor (positive constant).

The greater the value of v, the greater the concentration of flow, and Holmgren (1994) suggests

values between 4 and 6 for distributed modelling.

Throughflow represents subsurface water transfer in the saturated zone and is determined by

Darcy's law, as displayed in Equation 20.

Equation 20

$$tf_v = wt * y * K_d \frac{dh}{dx}$$

tf_v is the throughflow rate (m³ s⁻¹),
wt is the height of water table above bedrock (m),
y is the width of routing facet (m),
K_d is the soil conductivity at water table depth (m s⁻¹),
h is the hydraulic head (m),
x is the horizontal distance between model cells.

Soil conductivity changes with depth in the soil profile and is represented by Equation 21.

Equation 21

$$K_d = K_{sat} \exp(\frac{-d}{dc})$$

K_{sat} is the soil saturated conductivity,
d is the water table depth,
dc is the decay factor for change in conductivity with depth.

Channel network

Water movement in the channel is modelled using the Muskingum–Cunge model (Ponce & Lugo,

2001). Each reach is associated with a landscape cell and receives water from overland flow,

throughflow and upstream reaches. Outflow from a reach is determined by Equation 22.

Equation 22

$$Q = (C_0 * U) + (C_1 * U_1) + (C_2 * Q_1)$$

Q is the current discharge,

Q_1 is the previous timestep discharge,

U is the inflow from upstream reach,

U_1 is the inflow from upstream reach from previous timestep,

C_0, C_1 and C_2 are routing coefficients.

The network topology is determined from digital election model interpretation, producing flow

directions, gradients and upslope area. A landscape cell can be identified as a channel when the

upslope contributing area exceeds 0.8km^2, based on the value used in Lane et al. (2009).

Appendix 2.   Maps of intervention techniques used in CRUM3

The following maps present the recommended intervention techniques following simulation in

CRUM3.
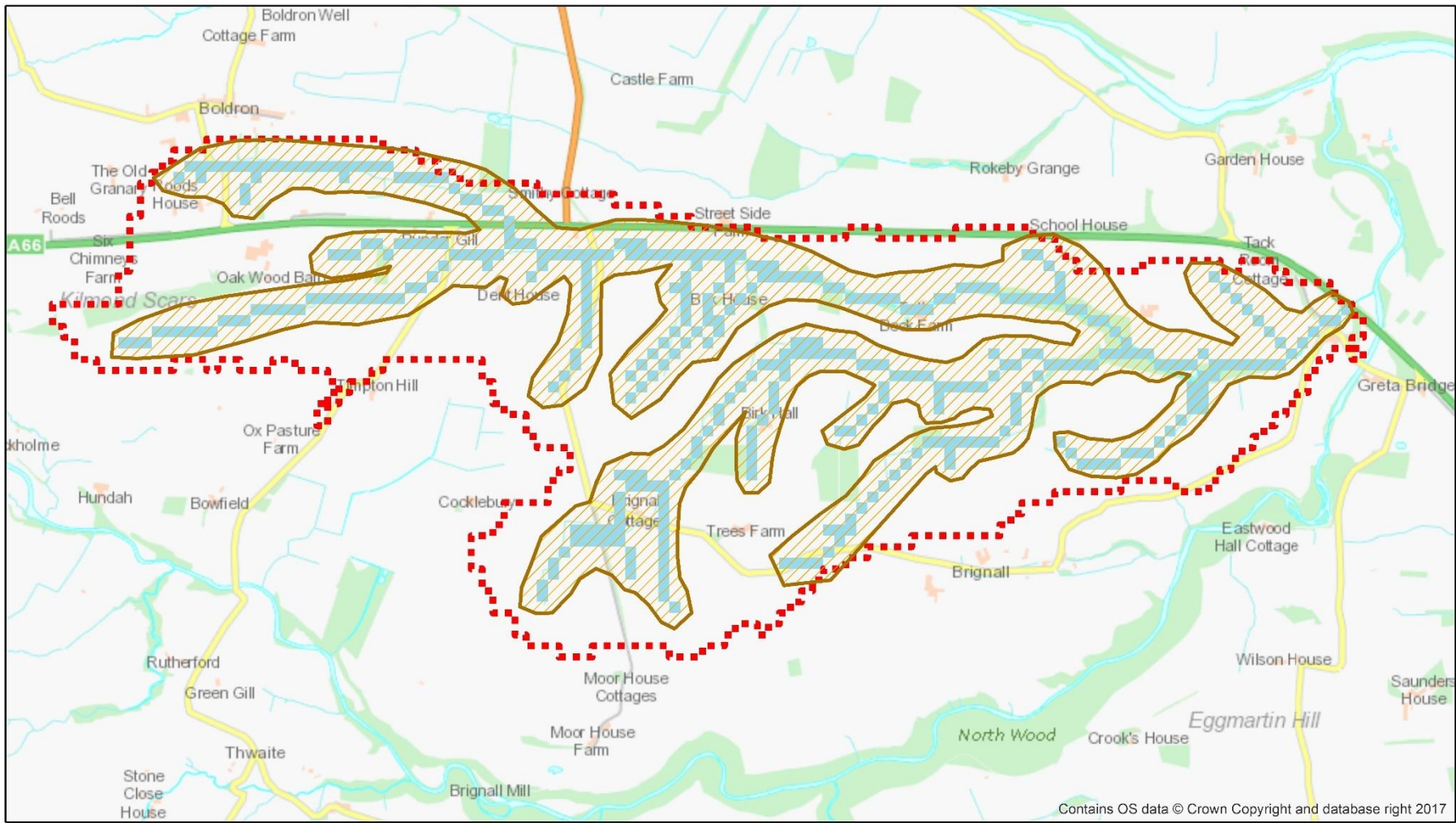
Legend

LCC buffering watercourses

Tutta Beck Catchment

Watercourses

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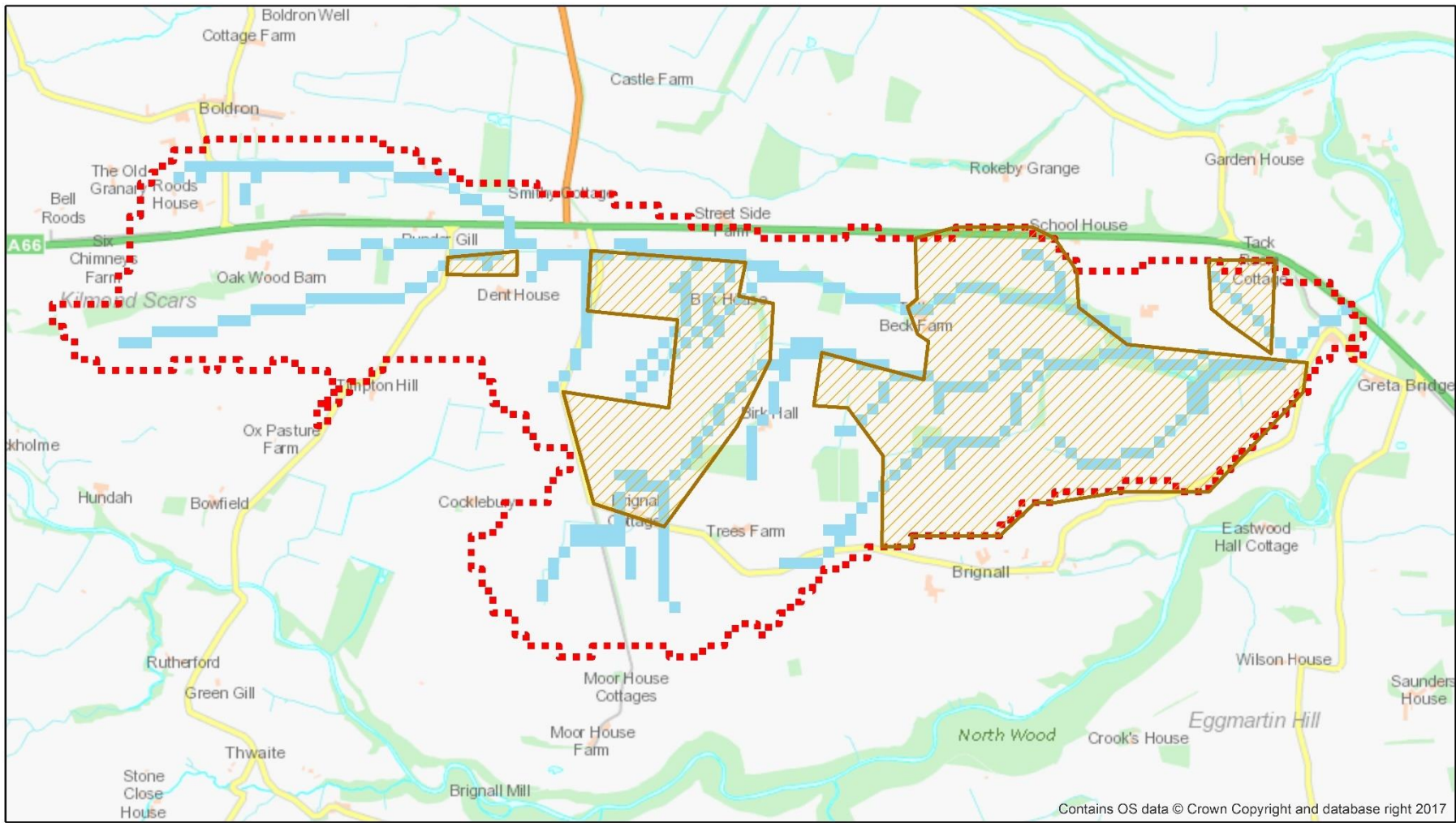
Legend

▨	LCC Arable to Broadleaf Woodland
▪▪▪▪	Tutta Beck Catchment
⬭	Watercourses

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230
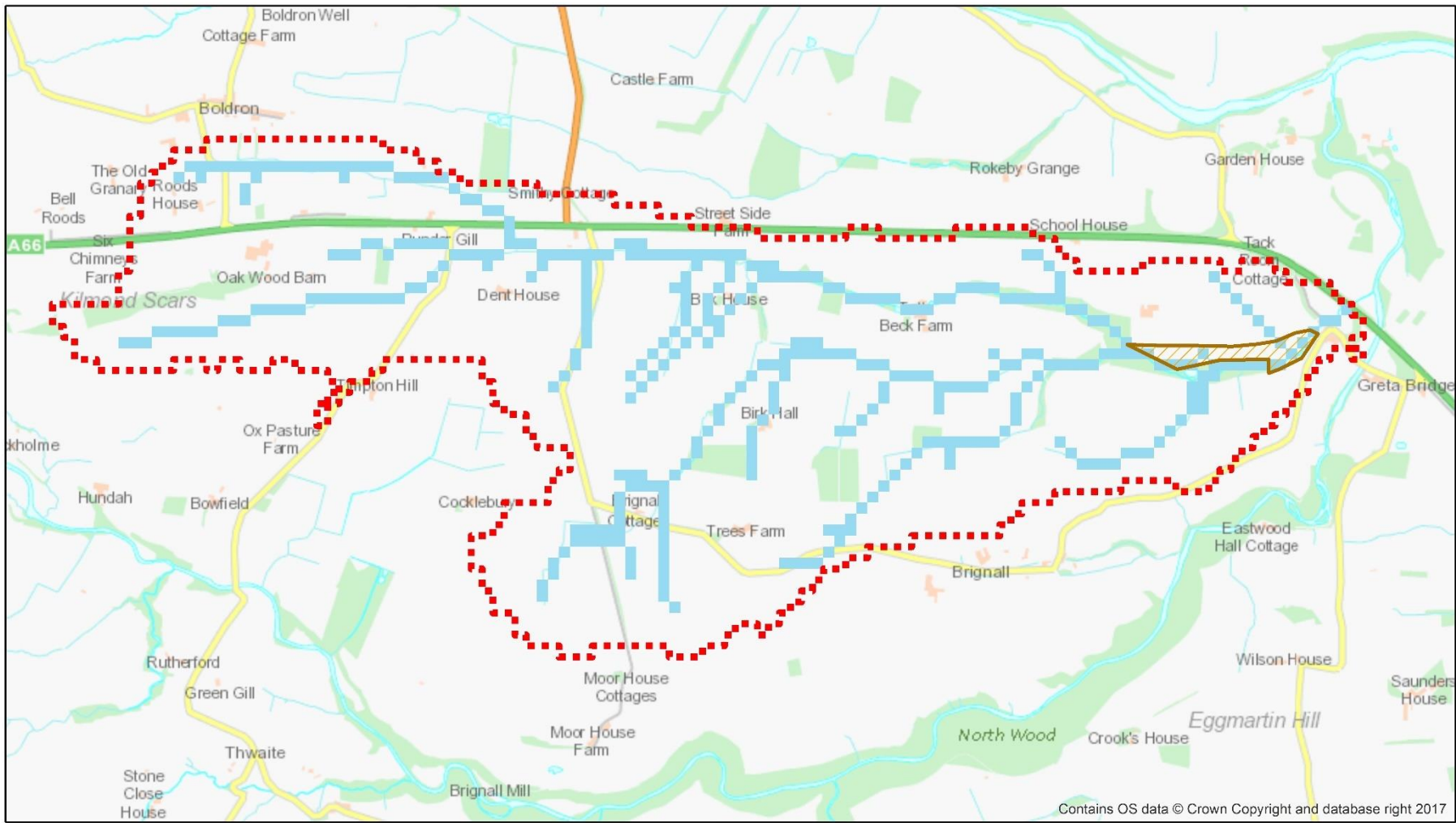
Legend

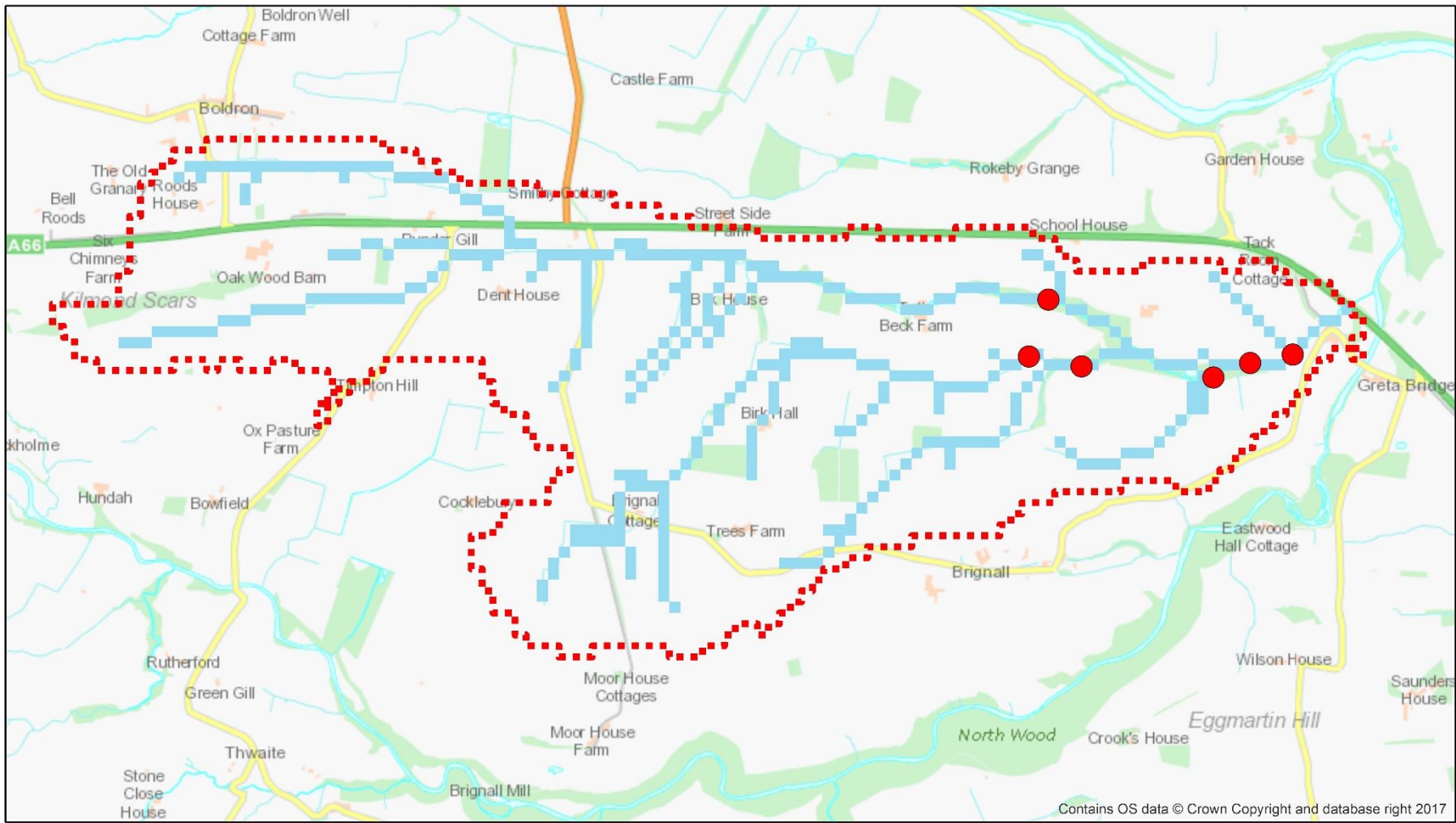LCC Catchment Sensitive Farming Option

Tutta Beck Catchment

Watercourses

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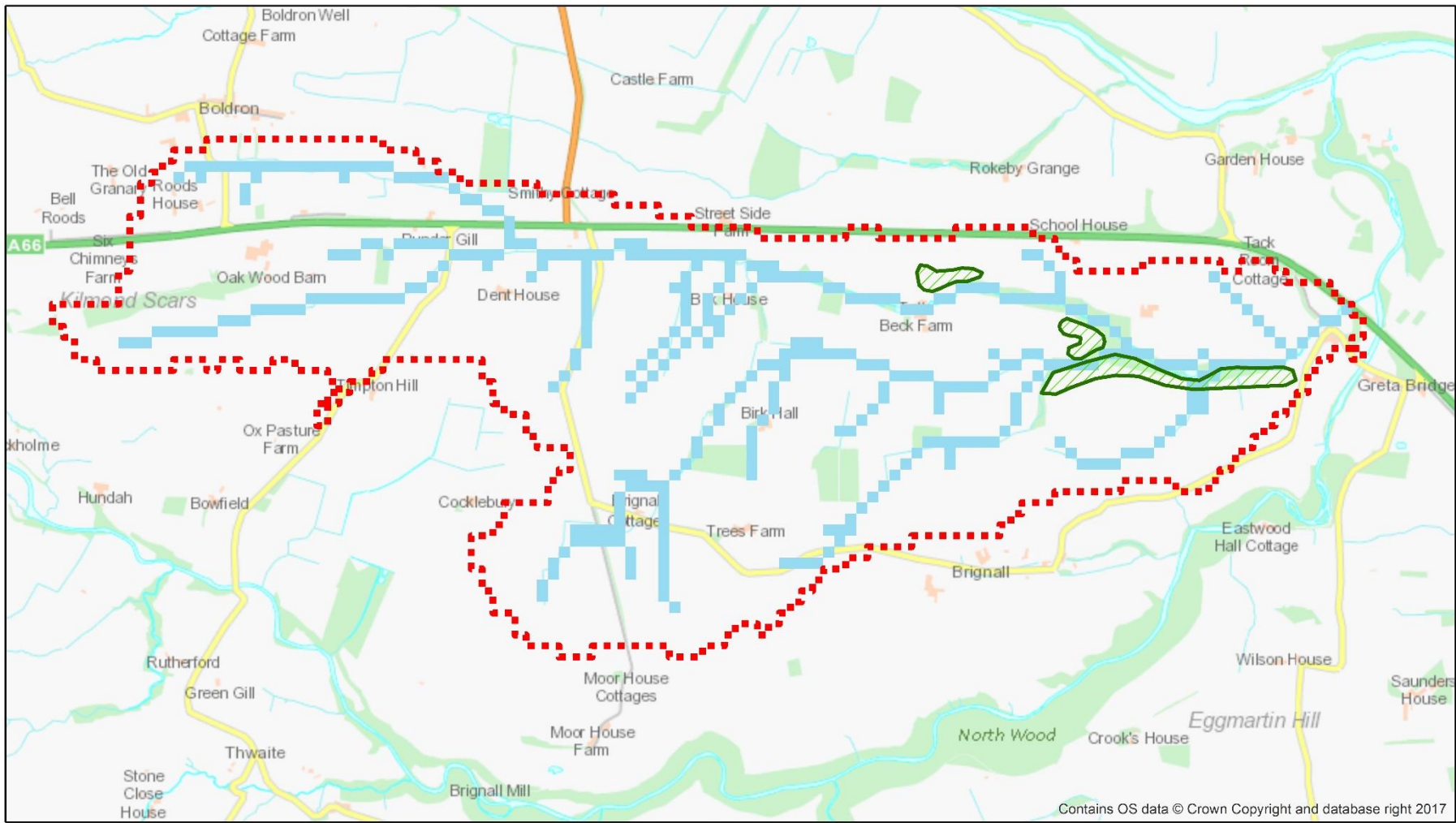
Legend

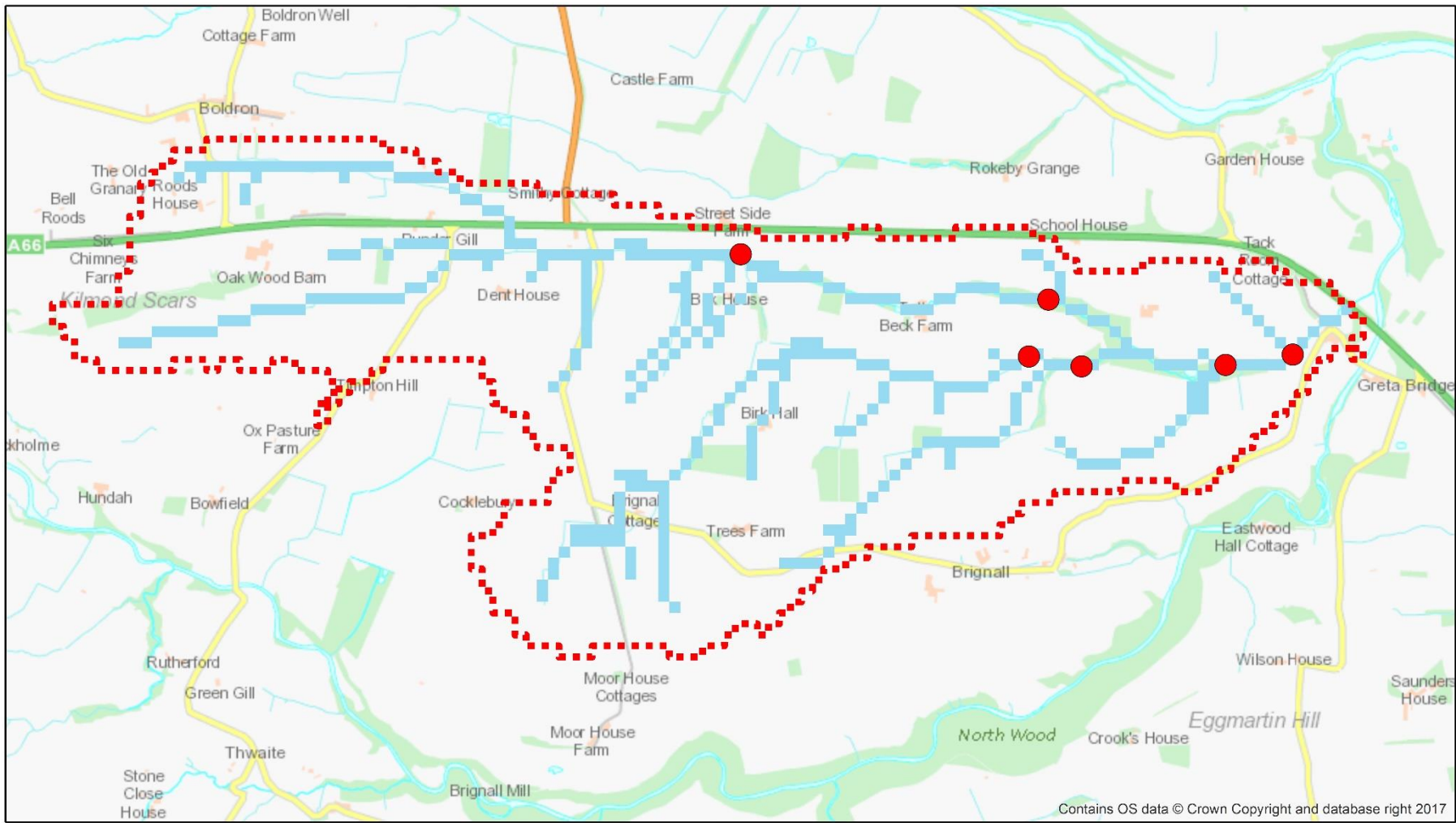Attenuation Driven by Land Cover

Tutta Beck Catchment

Watercourses

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Legend

Attenuation In South East of Catchment

Tutta Beck Catchment

Watercourses

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234

Legend

🔴 Large Wood Debris targeting floodplain

⬛ Tutta Beck Catchment

⬭ Watercourses

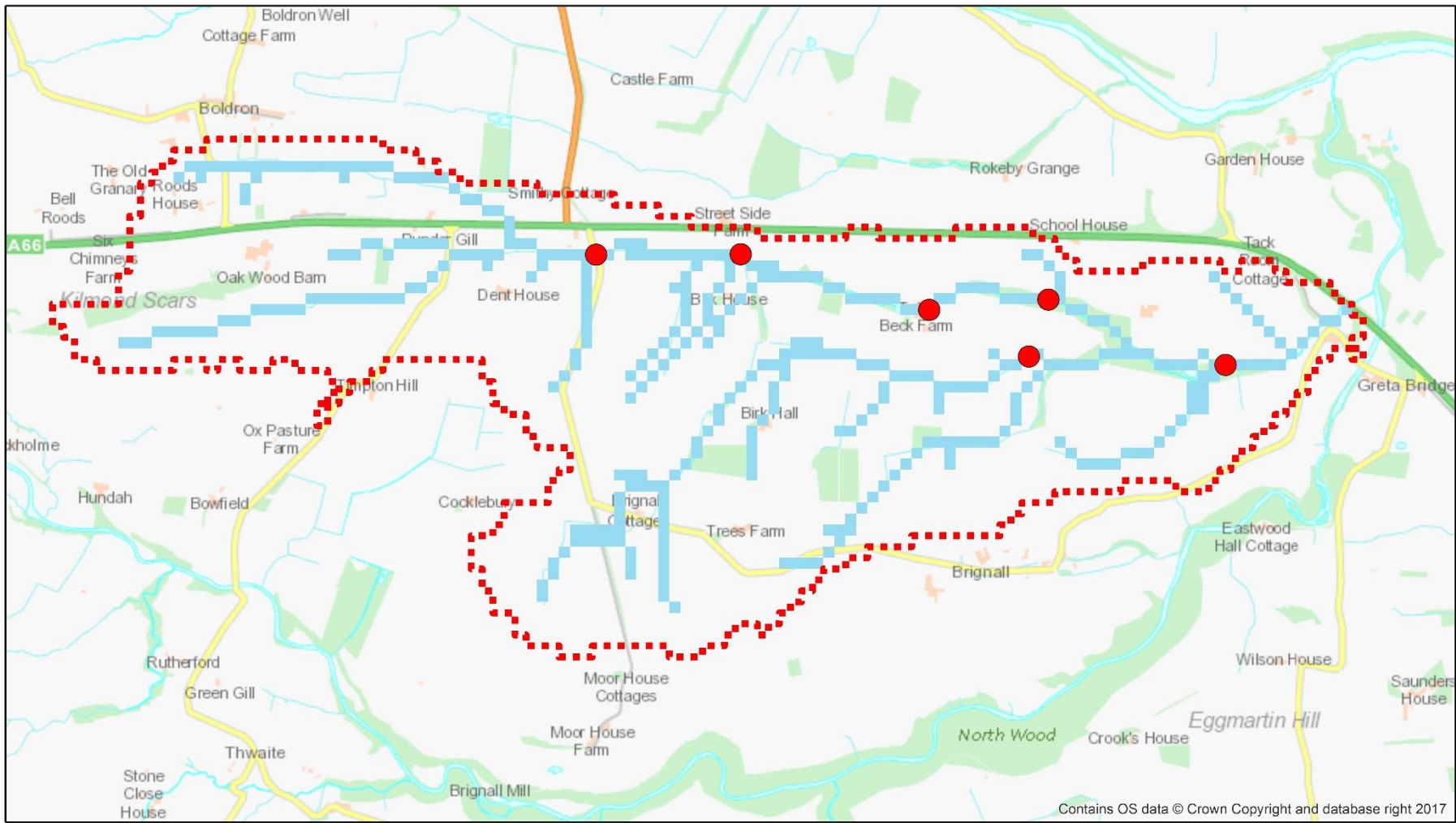Contains OS data © Crown Copyright and database right 2017

Legend

🔴 Large Woody Debris SCIMAP-Flood

▪▪▪ Tutta Beck Catchment

⬭ Watercourses

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Legend

🔴 Large Woody Debris Unused

⬛ Tutta Beck Catchment

⬭ Watercourses