DOCTOR OF PHILOSOPHY

Co-designing Opportunities and Modelling Performance of Catchment Scale Natural Flood Risk Management: Stour Valley, Warwickshire-Avon, UK

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Co-designing Opportunities and Modelling Performance of Catchment Scale Natural Flood Risk Management: Stour Valley, Warwickshire-Avon, UK

By

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Abbreviations

AEP	Annual exceedance probability
ALC	Agricultural Land Classification
ALTBAR	Mean catchment altitude
AOD	Above Ordinance Datum
AONB	Area of Outstanding Natural Beauty
BACI	Before-after-control-impact
BFIHOST	Base-flow Index Hydrology of Soil Type
BGS	British Geological Survey
CaBA	Catchment based approach
CBA	Cost-benefit analysis
CCA	Climate Change Allowances
CEH	Centre for Ecology and Hydrology
CFMP	Catchment Flood Management Plan
CSF	Catchment Sensitive Farming
DCLG	Department of Communities and Local Government
Defra	Department for Environment, Food and Rural Affairs
DEM	Digital Elevation Model
DPSBAR	Mean catchment slope
DRN	Digital River Network

DTM	Digital Terrain Model
EA	Environment Agency
ELS	Entry Level Stewardship
FARM	Floods and agricultural risk matrix
FCERM	Flood and Coastal Erosion Risk Management
FCERM-AG	Flood and Coastal Erosion Risk Management Appraisal Guidance
FD	Floods Directive
FEH	Flood Estimation Handbook
FIM	Flood Impact Modelling
FWMA	Flood and Water Management Act
GIS	Geographic Information Systems
GIUH	Geomorphological instantaneous unit hydrograph
HLS	Higher Level Stewardship
HOST	Hydrology of Soil Type
ICMP	Integrated Catchment Management Plans
IDB	Internal Drainage Boards
LCM2015	Land Cover Map 2015
LDA	Land Drainage Act
LFRMS	Local Flood Risk Management Strategy
LiDAR	Light Detection and Ranging

LLFA	Lead Local Flood Authority
MSfW	Making Space for Water
NaRFA	National River Flow Archive
NWRM	Natural Water Retention Measures
NBS	Nature Based Solutions
NFM	Natural Flood Management
NFRA	National Flood Risk Assessment
NFRM	Natural Flood Risk Management
OELS	Organic Entry Level Stewardship
OSMM	Ordinance Survey MasterMap
PDM	Probability Distributed Modelling
PIFs	Permanent Ineligible Features
POT	Peak over threshold
Q	Discharge
QBAR	Mean annual flow rate for a river
QMED	Index flood
R.SuDS	Rural Sustainable Drainage Systems
RAFs	Runoff attenuation features
RASP	Risk Assessment for Strategic Planning
RBMP	River Basin Management Plans

ReFH	Revitalised Flood Hydrograph
RFCC	Regional Flood and Coastal Committee
RPA	Rural Payments Agency
SAAR	Standard Average Annual Rainfall
SEPA	Scottish Environment Protection Agency
SFRA	Strategic Flood Risk Assessment
SPR	Standard Percentage Runoff
SuDS	Sustainable Drainage Systems
SWMP	Surface Water Management Plans
T_P	Time-to-peak
URBEXT	Urban extent
WFD	Water Framework Directive
WwNP	Working with Natural Processes

Abstract

Flood Risk Management (FRM) in the UK has undergone a paradigm shift in response to recent catastrophic flood events, particularly the June/July 2007 summer floods and the winter floods of 2015/2016 that affected much of Northern Britain, Northern Ireland and parts of Wales. Traditional engineered FRM techniques, such as river walls and levees, have historically been designed to increase conveyance in the water network, moving storm-flow downstream from the community at risk. However, more recently a holistic catchment systems approach targeting FRM activities in the farmed uplands, known as Natural Flood Risk Management (NFRM), has gained increasing prevalence in policy and practice. NFRM constitutes a wide variety of techniques that aim to alter the biophysical characteristics of catchment surfaces for a reduction in conveyance, attenuating the downstream peak through the manipulation of upstream storm-flows. Whilst advocated, there are large gaps in research and practice such as how receptive farmers are to altering their land management practices to slow, store, infiltrate and disconnect flood flows. These critical stakeholders are also recognised to provide valuable local knowledge and place-based thinking that can better inform where best to apply NFRM techniques. There is also a critical need for a better understanding of NFRM performance to provide much needed empirical evidence. This lack of quantification, especially at the large catchment scale, prevents such an approach becoming more widely adopted.

In this study a new, integrated Participatory GIS (PGIS) mapping framework has been devised and tested with 38 farmers across the study site in order to co-design NFRM, applying active engagement and local flood risk management (LFRM) communication methods. The digitised PGIS-NFRM scenario was tested against a distributed rainfall-runoff model to demonstrate the performance of the techniques to multiple hydrological scales and rainfall events. The research found farmers were variably receptive to having NFRM techniques applied to their holdings. Furthermore, there was considerable variation in the number and types of techniques identified, which was highly dependent on cadastral land use. The performance of the PGIS-NFRM techniques was also found to be variable based on event magnitude, antecedent conditions, sub-catchment timings of peaks and types of techniques applied. NFRM mainly demonstrated a reduction in flooding from smaller events, especially at small hydrological scales (<10km^2). However, it did not demonstrate significant flood risk benefits for larger events, especially at scales >100km^2. The study is the first of its kind to show how local knowledge can be incorporated into NFRM, and wider LFRM, decision-making. As a result it generates a transferrable framework for relevant agencies, river management authorities and catchment stakeholders to adopt when identifying NFRM opportunities and tests their performance across multiple hydrological scales and different rainfall events.

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1 Introduction: Research Framework and Aims

1.1 Working with Natural Processes for Natural Flood Risk Management

This study aims to investigate the potential impact of rural land management on catchment-scale flood risk, and the role working with natural processes (WwNP) and the stakeholders that apply them can play through a large scale application of Natural Flood Risk Management (NFRM). It is widely thought that flood risk has increased since records began, potentially entering a climatic Anthropocene period of increased flooding in the UK (Werritty 2002 and Lane 2008). Flood and coastal erosion risk management (FCERM) has become a top priority in the international hydrology community, and especially the emerging ethos of NFRM as a way of holistically managing catchment flood flows. Since the extensive UK flooding in July 2007, and more recently the Winter floods 2015/16 impacting the North-West and Cumbrian catchments, responsive reports including Pitt (2008), Environment Audit Committee (2016), and the Environment Food and Rural Affairs (Efra) committee (2016) have found climate change, urban creep and changing rural land management have detrimentally enhanced impacts from hydrological events (O'Connell *et al.* 2004). However, understanding these complex catchment dynamics at the large scale remains a challenge.

In relation to flood risk, much of the context for this research derives from Defra Multiple Objective Pilot Projects and Foresight Future Flooding Studies (Lane *et al*. 2007) that suggest there is a lack of understanding of how, and even if, the impacts on hydrological regimes from local changes in land management scale up to the whole catchment. Upscaling in this way has been recognised as a difficult task (O'Connell *et al.* 2004). The aim of this study is the development and application of an approach based on identifying and assessing opportunities for NFRM, through a novel Participatory Geographic Information System (PGIS) approach, incorporating local knowledge through community mapping and a co-design process, and then further hydrodynamic flood modelling to determine the performance of catchment-scale NFRM in terms of alleviating downstream flood risk.

1.2 Aims and Objectives

Aim 1: Desk-based characterisation of the Warwickshire-Avon catchment area

Objectives

1.1 Undertake a data-mining exercise, collating and reviewing remote data to inform hydrological, geological, pedological land cover and land-use characteristics of the catchment.

1.2 Physically, hydrologically and socially characterise the catchment in a GIS.

1.3 Generate clipped base-maps for each farm and estate of catchment characteristics to include in farm information packs (FIPs) for Participatory GIS (PGIS).

Aim 2: Co-design NFRM opportunities across the catchment area

Objectives

2.1 Actively engage with all landowners/farmers across the catchment to arrange PGIS exercises.

2.2 Identify sources and pathways of flooding on each participants' farm and/or estate.

2.3 Identify and co-design NFRM opportunities to address the sources and pathways of flood flows on each participants' farm and/or estate.

2.4 Digitise NFRM opportunities in GIS, and confirm with participants.

Aim 3: Model the performance of the PGIS-NFRM scenario to multiple storm events

Objectives

3.1 Build a large, delineated 1D/2D hydrodynamic-based model of the whole catchment area.

3.2 Generate FEH design storm input hydrographs (QMED, 3.3%AEP, 1%AEP and 1%AEP + 35%)

3.3 Calibrate model and FEH storms to observed flow data, including sensitivity analysis to identify and reduce uncertainty.

3.4 Simulate the baseline 'do nothing' scenarios, across multiple hydrological scales and flood risk events.

3.5 Simulate the PGIS-NFRM scenarios, identify and assess any benefits and/or disadvantages of NFRM across multiple hydrological scales and flood risk events.

1.3 Thesis Outline

Chapter 2 – provides a synthesis of the relevant literature including catchment processes, flood risk management, the policy landscape and working with natural process, including a systematic review of national and international Natural Flood Risk Management (NFRM) case-studies.

Chapter 3 – outlines the methodological approaches used to achieve the thesis aims and objectives. The research catchment and the associated research framework to co-design NFRM and assess performance in a hydrodynamic model to multiple periods are presented. The method of co-design NFRM using Participatory GIS (PGIS) are detailed, as well as the way in which observed data has been used to calibrate the modelling in order to test NFRM performance.

Chapter 4 – presents the results and lessons learnt from the pilot study farm investigation, testing the robustness and replicability of the PGIS method. The section provides the physical, hydrological and social characterisation of the area within the farm information pack (FIP), before detailing the methods of incorporating local knowledge into NFRM decision-making.

Chapter 5 – provides the results meeting the second aim, upscaling the PGIS method, co-designing and analysing catchment distribution of NFRM opportunities. Influential catchment characteristics (identified meeting the first aim) when considering potential NFRM opportunities.

Chapter 6 – uses the hydrodynamic FEH rainfall-runoff model to test NFRM performance across a variety of hydrological scales and flood risk scenarios. Investigating changes in flood peak (Qp) and associated times-to-peak (Tp) in river responses.

Chapter 7 – discusses the results of both the NFRM opportunities (second aim) and performance testing (third aim), in relation to other NFRM case-studies and wider significance on flood risk management policy and practice.

Chapter 8 – the final chapter concludes the thesis by evaluating the findings against the aims and objectives, provided in section 1.2, and provides recommendations for further work.

2 Flooding, Governance and Working with Natural Processes

2.1 Chapter Scope

This chapter provides a review of the current causes and risks of flooding, including meteorological and land-based conditions that intensify flood generation and morphological degradation of fluvial catchments (Smith and Ward 1998, Hannaford and Marsh 2007). The chapter will take a UK-centric view of the problem of flooding and review the complex trends that have enhanced risk in the 21st century (Sear *et al.* 2015); this includes physical factors of climate change, urban creep and, of particular relevance to Natural Flood Risk Management (NFRM), the intensification of agricultural land management (Sayers *et al.* 2012, Dawson *et al.* 2011, Pattison *et al.* 2014). Flood risk management (FRM) policies and practices are also discussed, including the shift in governance and rise of localism in FRM decision-making (Twigger-Ross 2014, Environment Agency 2009).

In response to the extensive 2015-16 UK winter floods, multiple reviews identified a need to better understand the meso-scale influences of agricultural contributions to flood risk, and what role farmers, landowners and land managers can play as key stakeholders in catchment management (Foundation for Common Land 2016, Priestley 2016, Szönyi *et al.* 2016). This chapter will frame the discussion of flooding in terms of the role of Working with Natural Processes (WwNP) schemes as a tool in the portfolio of measures to manage flood risk more strategically (Pitt 2008, National Audit Office 2014), and in particular the variety of NFRM methods applied in non-tidally influenced fluvial catchments. The chapter is comprised of two sections: Section 1 provides an analysis of issues relating to fluvial flooding in the UK, with consideration of political and practical FRM agendas in an English context; Section 2 includes a meta-analysis of studies investigating land-use alteration through the use of NFRM methods. Whilst there is a growing body of literature concerned with NFRM's ability to provide multiple ecosystem services (Vermaat *et al.* 2016, Iacob *et al.* 2012, Natural England 2015, Mellor 2014), the regulatory function and operational methods of FRM are the focus of this study and therefore have been the key elements identified from the literature.

2.2 Flood Risk: A UK Perspective

2.2.1 Defining Flood Risk

It is widely recognised in both public and professional spheres that the frequency and magnitude of flooding is increasing, with currently 1 in 6 properties at risk of flooding in England and Wales (Environment Agency 2019). Natural rivers have always been the centre of civilisation, providing convenient access routes, sources of power, drinking water supply, irrigation for agriculture and soil fertility - for these reasons society has historically outweighed the possible risks of flooding against those benefits (Knight 1978, Mauch and Zeller 2009). However, changes to institutional infrastructure have altered what society values in this cost-benefit ratio (Meyer, Priest and Kuhlicke 2012). Industrialisation, urbanisation and agricultural intensification to feed a growing population have led to the large-scale disconnection of floodplains from rivers that have been straightened, deepened, culverted and embanked, increasing downstream conveyance (Peacock 2003); currently less than 20% of Europe's floodplains and rivers are considered as naturally functioning (Blackwell and Maltby 2006). Developed civilisations now expect high 'standards of protection' (SoP) to the natural hydrological process of flooding to ameliorate the risks river processes and flooding pose to modern infrastructure (English Nature 2006).

Since the Future Flooding Project (Evans *et al.* 2004) and the EU Floods Directive (2007) there has been a shift towards better understanding flood *risk* beyond the *hazard* of flooding, with the advancement of tools to improve the understanding of portability as a spatial distribution (defined as likelihood) and consequences (impacts), illustrated in Equation 2.1, further discussed in Section 2.2.2.

$$\text{Risk} = \text{Probability} \times \text{Consequence}$$

Probability: the likelihood of an event, commonly referred annual exceedance probability (AEP)

Consequence: the subsequent impacts of varied probability events, principally economic

Equation 2.1 Calculating risk (GFDRR 2012, Ramsbottom et al. 2006, Bowker 2007)

2.2.2 Current Flood Risk

In England and a large proportion of economically-developed world, flood risk (indiscriminate of source) predominately manifests as economic damages to properties and businesses (Sofia *et al.* 2010). Whilst in exceptional events risk to life is not uncommon, in the last century 437 deaths in the UK have occurred as a result of flooding, approximately 70% from the 1953 North Sea Storm (Defra 2015 and RMS 2015). In the same period flooding has conservatively cost the UK economy £140 billion (modern valuation) as a result of damaged assets, clear-up costs, loss of personal income, loss of business continuity and insurance claims (Chatterton *et al.* 2008, Evans *et al.* 2004, Doocy 2013, Sofia *et al.* 2010). In England, the Environment Agency undertook a nation-wide National Flood Risk Assessment (NaFRA) in an effort to assess the current exposure to fluvial and pluvial flood risk nationally using the source-pathway-receptor (SPR) methods (Environment Agency 2008a). In order to quantify these risks the Modelling Decision Support Framework 2 (MDFS2) strategic asset performance tool provides probabilistic flood extents that accounts for existing flood defences, originating from the Environment Agency's Risk Assessment for Strategic Planning (RASP) R&D Project (Environment Agency 2003, Sayers and Meadowcroft 2005, Flikweert *et al.* 2015).

Figure 2.1 outlines how the MDFS2 software processes data in order to identify risk, specifically spatial outputs of flooded extents and depths behind the line of defence. This provides a powerful and nationally strategic visual tool of the exposure and subsequent damages of a flood event, with greater depths commonly leading to greater damages (Penning-Rowsell *et al.* 2015). However, Simm (2008) notes it does not include all the factors known to affect asset performance and fragility. For instance, it does not simulate natural processes, such as sediment transport, and the probability of asset failure during multiple peaked flood events. The importance of this omission is evident in the Brompton flood alleviation scheme (Metcalfe 2017), where flood risk schemes were adversely affected by double-peaked flood hydrographs and the capacity of traditional flood storage areas were reached and exceeded before draining for the subsequent peak (Lamb *et al*. 2010)

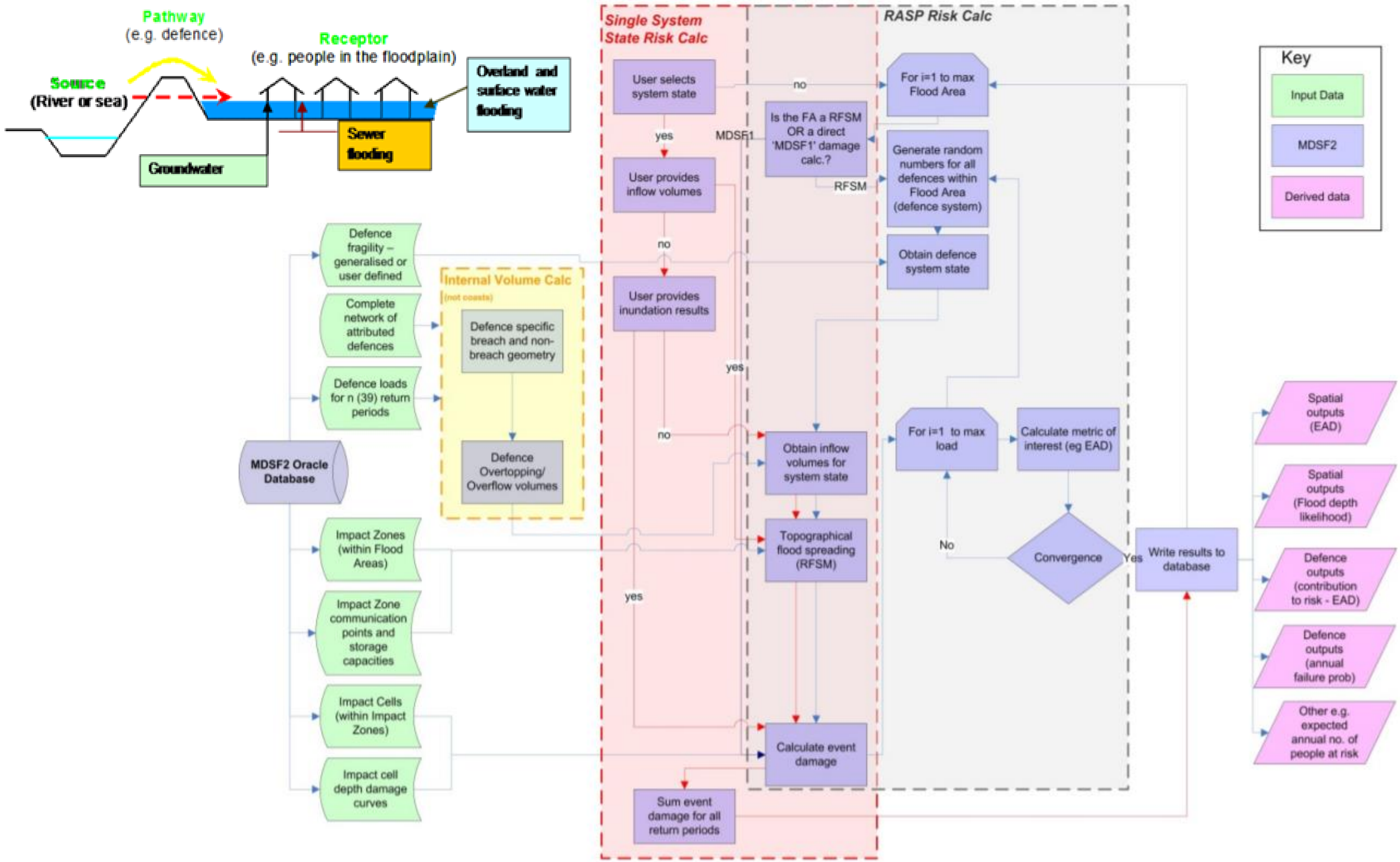

Figure 2.1 The MDFS2 data processing framework for the quantification and spatial representation of risk (adapted from Environment Agency 2009a)

Using the MDFS2 tool (Figure 2.1), Figure 2.2 identifies the number of properties and businesses at risk to different magnitude and frequency events. The highest number of those at risk are located in the Greater London area (542,000 properties – approx. one million people). However, the same area also has the lowest percentage of properties at 'significant risk' due to the highest investment in defence infrastructure (Lavery and Donovan 2005, Thames 21 2015).

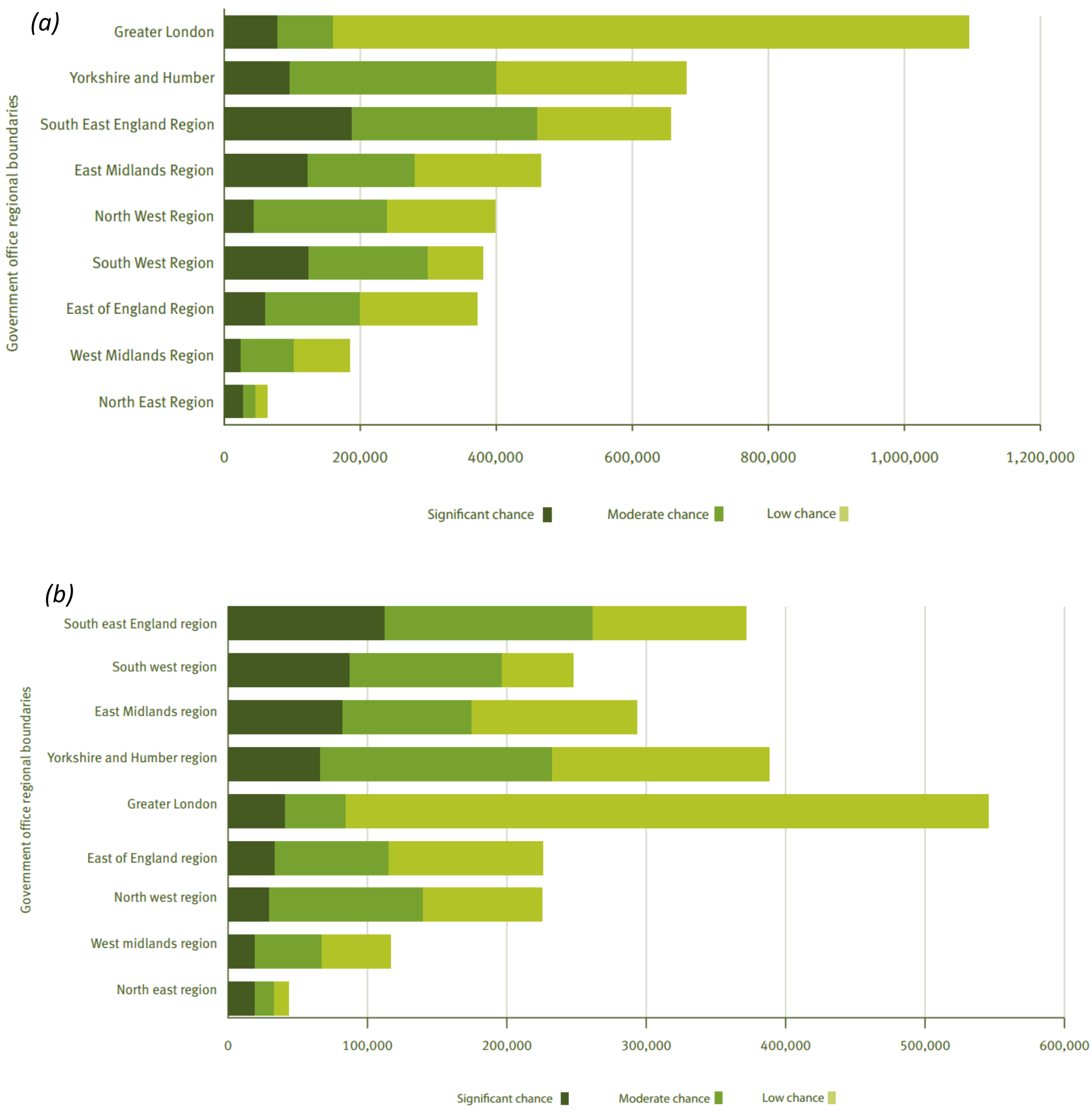

Figure 2.2 Regional and local fluvial flood risk patterns. (*a*) Regions ranked by the number of people living in the floodplain. (*b*) Regions ranked by the number of properties at significant risk of flooding (Environment Agency 2009b).

As mentioned in Section 2.2.1, flood risk is often defined by likelihood - the NaFRA bandings of risk are based upon the annual exceedance probability (AEP) in any given location, not the consequences. Low (<0.5 %AEP), Moderate (0.5 – 1.3 %AEP) and Significant (>1.3% AEP). However, it is important to recognise that as soon as data was gathered for the NaFRA, this snapshot was immediately out of date. The underlying pressures and drivers and the flood risk management decisions in response to them are continuously changing (Simpkins 2017).

Furthermore, based on Bennet *et al.* (2015) forecasts, England's current approximate £1.1 billion annual flood damage costs are anticipated to rise to as much as £27 billion by 2080, with existing maintenance levels of flood defences requiring flood defence spending to increase to over £1 billion per year by 2035 in order to maintain existing levels of risk.

Recent floods have increased focus on developing more cost-effective and sustainable flood management policies (e.g. ICE 2001, EEA 2008, Defra 2004a, Pitt 2008, Efra 2016). The extensive winter 2015/16 floods that impacted much of Northern Britain, Northern Ireland and parts of Wales as a result of storms Desmond, Eva and Frank provided impetus for a more proactive approach in adapting catchment surfaces to the risks of flooding (EAC 2016). Previous UK events, including the July 2007 floods (Chatterton *et al.* 2010), the Central England floods in Easter 1998 (Horner and Walsh 2000), Boscastle 2004 flash flooding (Golding *et al.* 2005), and Carlisle January floods 2005 (Environment Agency 2015), indicate the increasing threat from such intense rainfall events. However, analysis of long-term rainfall data does not detect a long-term transformation in spasmodic (spatially varying) standard annual average precipitation totals since the eighteenth century, as shown in Figure 2.3 (data sourced Met Office 2017). During this period however, the UK has undergone a variation in rainfall seasonality with a notable escalation in winter precipitation and a decrease in summer. The dense meteorological observation network of the UK also identified precipitation in the form of rainfall in the uplands increasing more than in lowlands. These current trends (highlighted in Figure 2.3) indicate the UK is in a 'flood-rich period' (Burt *et al.* 2015) associated with prolonged low pressure systems and westerly airflows. Since the late-1990s Sutton and Dong (2012) suggest the current flood-rich period has also been heavily ascribed to warming conditions in the North Atlantic Ocean. The updated UK Climate Projections 2018 (UKCP18) suggest coastal flooding will increase under all scenarios, with mean sea level rise around the UK between 0.29 – 1.12m (Lowe *et al.* 2018). Whilst more inland precipitation is not consistently projected, there is a greater likelihood of precipitation falling as intense storm events, increasing the likelihood of larger flood events (Hall *et al.* 2009).

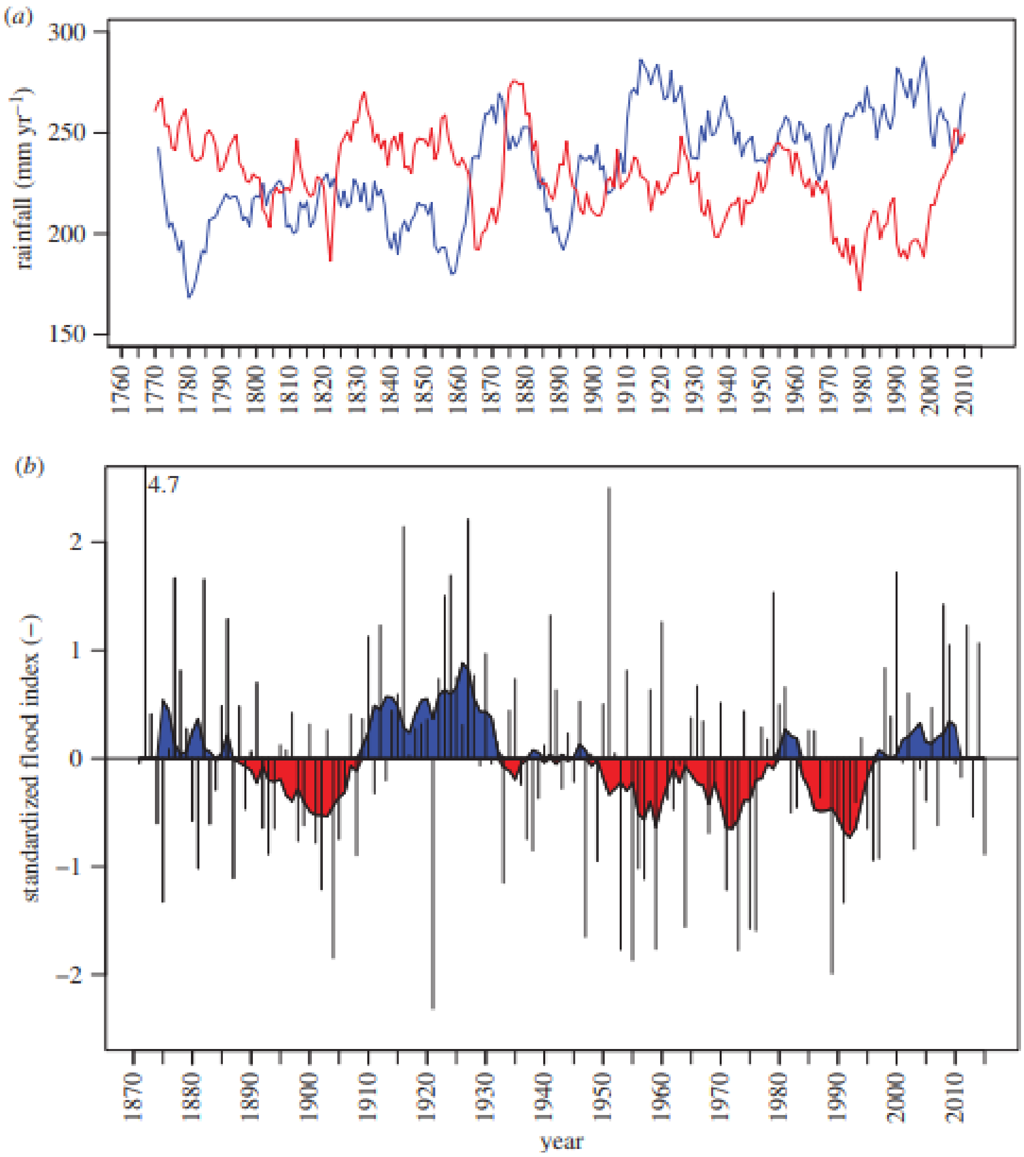

Figure 2.3 Climate trends and flooding patterns. (*a*) England and Wales rainfall seasonality (1776 – 2015); blue lines indicate winter rainfall and red lines summer rainfall (data sourced: Met Office 2015). (*b*) Annual mean flood index (1871 – 2015). The blue and red shading shows flood-rich (blue) and flood-poor (red) periods (Dadson *et al.* 2017, data sourced: Lamb *et al.* 2015, Climatic Research Unit 2015).

Robson's (2002) and Sene *et al.'s* (2015) findings support Figure 2.3 (b), which identifies data from the last 70 years indicating trends of increased fluvial activity, with floodplains increasing in use and having a higher level of impermeability, leading to greater levels of flood risk. A study by Fielding *et al.* (2011) across the Severn River Basin District showed hard-engineered schemes (e.g. flood walls) designed to a specified return interval event (commonly 1 in 100/1%AEP) should be re-assessed, as it is likely the assumption of stationary flood frequency has fluctuated with climate change and wider land cover change, including urban creep and agricultural intensification, reducing the effectiveness of the schemes (similarly found in Milby *et al.* 2008). Whilst urban creep is widely considered the most detrimental land cover change to enhance risk, with increased exposure to flood waters (especially development in floodplains) and conversion of land to impermeable surfaces (Hall *et al.* 2014, Miller *et al.* 2014), the intensification of the farmed environment and agricultural land use has led many researchers to explore the effects of increased agricultural productivity (O'Connell *et al.* 2007, McIntyre *et al.* 2013). These intensification practices such as ditching, under-drainage, cereal crop growth, larger machinery use and over-grazing will be discussed further in Section 2.4.

The latest climate change projections from UKCP18 and global models from the Intergovernmental Panel on Climate Change (IPCC) do not indicate a significant variation in annual precipitation totals across the UK between present and the upper 2080 epoch (80% of simulations indicate ± 16 % in rainfall). Regionally, climate models indicate some change in spasmodic rainfall patterns, with a projected rise in winter precipitation on England's westerly basins between + 9% and + 70%, and summer precipitation decreasing across the southern extent of England between -65% to -6% for the same period. However, increased precipitation maxima volumes during storms (especially in the summer) are expected to be more frequent. Warmer temperatures means totals of upland precipitation in the winter may also rise due to current projections as winter precipitation is projected to fall as rain instead of snow, thus further impacting river flows with increased likelihood of snow melts and localised flash flooding (Dadson *et al.* 2017, Sayers *et al.* 2015).

Flooding occurs from multiple sources and it can often be challenging to differentiate the main cause of a flood event without an understanding of the catchment, rainfall event and antecedent conditions. In England, the most common causes of flooding and proportion of risk is outlined in Table 2.1 below.

Table 2.1 Main sources of flooding and number of properties and business at risk in England, as determined from the National Receptor Dataset (NRD) (Environment Agency 2005; 2019).

Flood sources and descriptions	No. of properties at risk
River (fluvial) flooding occurs when a channel exceeds bank full capacity and inundates the surrounding land. For example, when a heavy rain fall events occurs in an already saturated catchment.	2 million
Coastal flooding occurs from an amalgamation of factors, most notably high tides and storm surges. If high tides occur with low atmospheric pressure, a coastal surge may occur.	400,000
Surface water (pluvial) flooding occurs when heavy precipitation overwhelms the existing drainage capacity within a localised drainage basin. There are difficulties in its prediction both in time and space.	3.8 million* *500,000 also at risk from rivers and sea
Sewer (surcharging) flooding occurs when the arterial sewerage network is overwhelmed by heavy precipitation and/or when blockages occur. The impacts and likelihood of sewer flooding is governed by the capacity of the sewerage network. Pollution to rivers and seas are a considerable concern of these events.	5000* *Based on Heather *et al.* (2008)
Groundwater flooding occurs when groundwater levels rise and appear on the lands surface. These events most commonly occurs in areas of perched aquifers, underlain by permeable geology. These sources of groundwater flooding can be extensive (regional aquifers) or local less permeable rocks in the base of valleys.	424,000* *Based on BGS (McKenzie and Ward 2015)

2.2.3 Catchment Systems: Land Cover, Agricultural Land Management and Flooding

In order to better understand the fundamental processes of flooding, hydrologist have undertaken extensive research on catchment systems, hill-slope hydrology, flow regimes, flood patterns, land cover and land management (Beven and Wood 1993, Robinson *et al.* 1995, Bloschl and Sivapalan 1995, O'Connell 2004, Blotchl *et al.* 2007, Beven 2012, Pattison *et al.* 2014 and Zoccatelli *et al.* 2015). However, Table 2.2 outlines the key research and development gaps on the effects of agricultural land management on flooding. This section will explore these R&D gaps in more detail, providing a review of the influential hydrological parameters, altering flood generation and propagation of flood waves in the river network.

Table 2.2 Research and development gaps in flooding and hydrological catchment processes

	R&D gaps	**Key sources**
Increasing uncertainty – reduced evidence	The level of contribution from a cell of land at the local hydrological scale ($<10km^2$). In terms of NFRM and WwNP this relates to the effects of farm/site-scale changes in land management and drainage practices.	De Roo *et al*. (2003), O'Connell *et al.* (2007), Oudin *et al*. (2008), Archer *et al.* (2010), Nicholson *et al.* (2014)
	The possible upstream influence in the surrounding area by increasing volumes and levels of water on one altered cell of land, principally the effects of backwater and flow synchronisation.	Ewen *et al.* (2015), Wheater *et al.* (2006), Jackson *et al.* (2008) and O'Donnell *et al.* (2011).
	The up-scaled influence of heterogeneous changes in runoff patterns at the meso-scale (large hydrological scale $> 100km^2$). The effects on flood flows across the whole catchment.	McIntyre and Thorne (2013), Pattison and Lane (2012), Bulygina *et al.* (2013), Ewen *et al.* (2013), Parrott *et al.* (2014)

The implications of local contributions have been investigated in studies of overland flood flows at the small catchment scales (<10km^2) (Wheater and Evans 2009, Nicholson *et al.* 2012 and Beven *et al.* 2008) with varied effects noted (see Section 2.5). However, studies investigating the meso-scale influences are less common, and often identify diminishing effects as a result of hydrological dilution and complex sub-catchment interactions (Dadson *et al.* 2017, Milly *et al.* 2008, Hankin *et al.* 2016). Hydrological scale refers to the sized order of magnitude of a catchment, defining a process, model or monitoring network (Bloschl and Sivapalan 1995). Whilst these scales vary both temporally and spatially, hydrologist tend to consider Klemes (1983) definition of hydrological scales as a reference of area, provided in Figure 2.4.

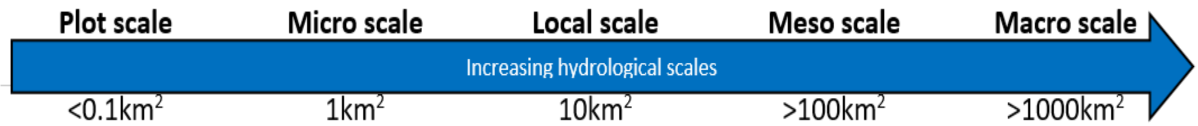

Figure 2.4 Definition of scales within catchment hydrology

The complexities in hydrological scales are evident in Figure 2.5. In areas at fluvial flood risk the storm flow - the response of the river as a result of a rainfall event (Shaw *et al.* 2011) - could be due to one or a combination of the following three hydrological processes:

I. A specific tributary had a large runoff response which caused a flood peak (Qp);
II. All tributaries responded with a larger than average Qp, or;
III. Synchronised individual tributary responses, converging flood flows through the network.

Within these hydrological processes there are multiple attributing factors that can also enhance catchment and river response to a rainfall event, either enhancing or ameliorating the flood peak. These factors fall within the two fundamental components that generate flooding, rainfall and runoff, outlined in Figure 2.5 below (adapted from Beven *et al.* 2014).

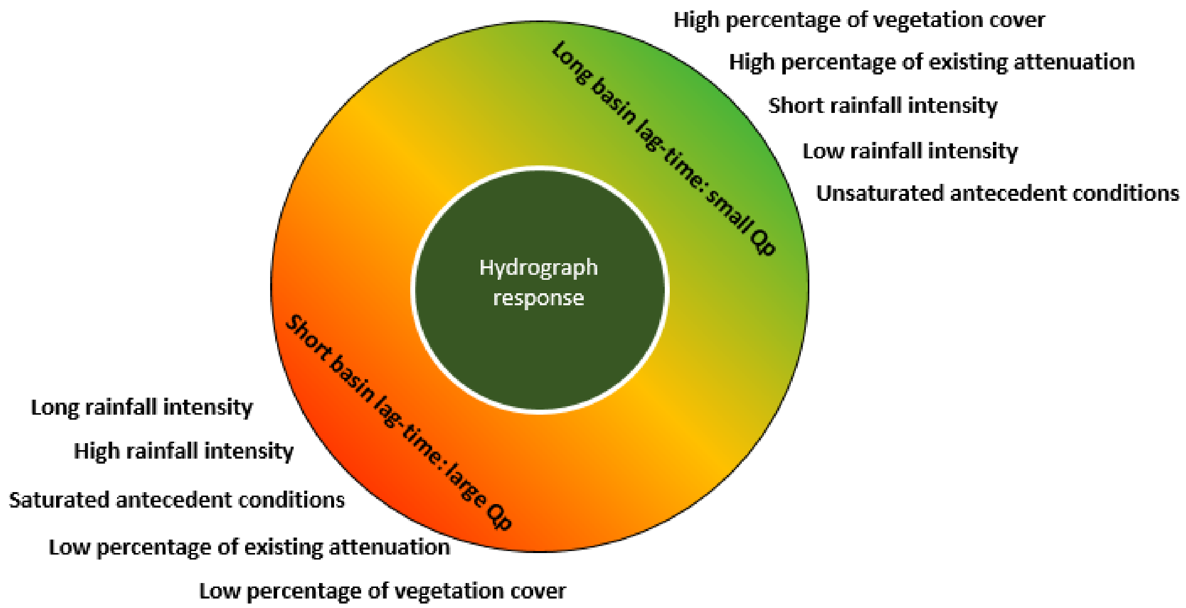

Figure 2.5 Hypothesised storm flow response to changing rainfall and catchment surface parameters

Not included in Figure 2.5, but also recognised to alter macro flood wave prorogation processes, especially at larger hydrological scales, is the shape of the catchment (Pattison *et al.* 2014, Zoccatelli *et al.* 2015). Figure 2.6 outlines the different catchment shapes and their common effect on downstream hydrography response. Principally, catchments with linear structures (parallel, rectangular and trellised) have a short lag-time, reduced time-to peak (Tp), with increased flood wave propagation. Catchments with complex tributary structures and meandering channels (dendritic and deranged) have longer lag-times, and increased Tp (Marshall *et al*. 2009, McIntyre *et al*. 2013).

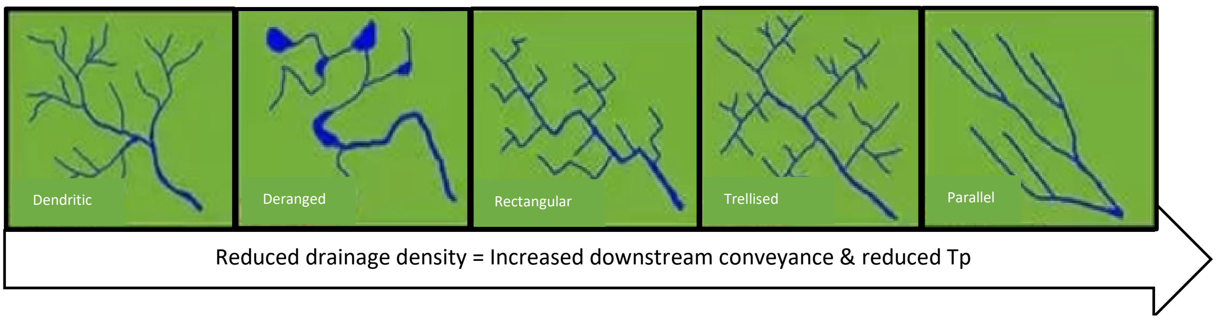

Figure 2.6 Common catchment shape effects on flood flows (adapted from Shaw *et al*. 2011)

UK land use and associated cover has changed drastically due to anthropogenic influence; woodlands and forest covered considerable areas of the UK in prehistoric times, but declined to approximately 6% in 1930, whilst now increasing to 12% (O'Connell *et al.* 2007). Whilst this review is most concerned with the effects of the agricultural environment on flood risk, the Flood Studies Report (FSR) and most recently the Flood Estimation Handbook (FEH) concluded (from catchments investigations across 553 and 943 sites, respectively) urban extent (URBEXT as referred to in FEH) was the single most significant factor that correlated to the magnitude of the mean annual flood (QMED) in UK rivers (McIntyre *et al.* 2013, Burgess-Gamble *et al.* 2016). Furthermore, numerical modelling employed in the Thames suggested that the influence of land cover modifications on downstream river flow is minor compared with expected climatic variability (Marsh and Harvey 2012, Hannaford 2015).

However, agricultural land management has intensified over the past 70 years (Holman *et al.* 2003, Wheater and Evans 2009, Palmer and Smith 2013, Defra 2016), manifesting in the loss of woodlands, hedgerows, enlarged fields for larger and heavier machinery, and conversion of grassland to arable fields. The conversion to arable land use has led to the ubiquity of surface and arterial field drainage (Figure 2.7) increasing hydrological connectivity from the farmed environment to the receiving watercourse and subsequent downstream urban areas (Bailey and Bree 1980, Robinson and Armstrong 1988, O'Connell *et al.* 2007).

Figure 2.7 Arterial drainage practices at the farm/site scale (O'Connell *et al*. 2007)

Agricultural land management studies provided evidence of flooding impacts at the local scale, commonly referred to as 'muddy floods' (Holman *et al.* 2001, Archer 2003, Beven *et al.* 2006, Heathwaite *et al.* 2005, Jackson *et al.* 2006, Environment Agency 2012). However, currently little empirical evidence suggests hydrologically local alterations in land use and thus runoff generation processes proliferate to larger hydrological scales downstream. This omission of evidence does not imply there are no impacts, but the limited studies into these complex hydrological processes have not produced any conclusive results, including Nant Barrog, Wales (Sisson 2018) and Low Stanger Farm, West Cumbria (Creighton 2015). Catchment assessment at multiple hydrological scales, linked to novel modelling approaches, is necessary to ascertain an improved insight into how highly distributed, local changes to land use can effect runoff generation processes to larger (particularly meso) catchment scales (Defra 2004, Defra 2011).

Studies examining agricultural land use and management practices often tend to focus on crop yield, and few explicitly assess associated runoff effects. Where runoff processes are investigated, it is normally to understand and mitigate sediment and nutrient transfer (Chambers *et al.* 1992, Fiener *et al.* 2005, Reaney *et al.* 2016). The Environment Agency FD2114 (2004) reviewed many of these studies, including the Rowden and Brimstone Farm project which examined the influence of different cultivation techniques on land drainage; Burt and Slattery (1997) undertook a localised (field scale) investigation in Oxfordshire of the River Stour, and Clements *et al*. (2003) investigated the role of compaction and saturation excess overland flows in a maize field at Frithlestock, North Wyke and Long Ashton. Since FD2114 (Environment Agency 2004), many projects have started to address evidence gaps by providing further evidence of influences on rainfall-runoff processes from the local to larger catchment scales. However, only a relatively few available studies have rendered (or are exploring how to expand) the results with local stakeholders by working with farmers to identify areas of high hydrological connectivity risk and WwNP opportunities (Wilkinson *et al.* 2013, Wilkinson *et al.* 2015, Burgess-Gamble *et al.* 2016). These studies (many of which are ongoing) have been collated and reviewed based on their aims, methods and results (including any engagement) in Section 2.4.2.

2.3 Flood Risk Management: Strategies, Governance and Decision-Making

The assessment and management of flood risk is undertaken through a complex network of international and national policies and mechanisms. This section will outline how flood risk is currently managed through a historically reactive approach (Werrity 2006, Efra 2016). This will cover how strategic policies and agendas relate to practical application through the planning system and governance structures when it comes to the ownership of risk and scheme delivery. This section will then focus on wider catchment management and the role of FRM stakeholders in WwNP and NFRM.

2.3.1 Evolution of Flood Risk Management

Broadly, the responsibility of the UK's current flood risk management (FRM) is devolved to agencies in England (Environment Agency), Scotland (Scottish Environment Protection Agency), Wales (Natural Resource Wales) and Northern Ireland (Department of Agriculture and Rural Development), as well as being differentiated between the organisations that manage the elements/sources of flood risk within each devolved administration (Heard *et al.* 2011). Figure 2.8 shows English agencies, which enforce regional, national and international agendas (Shaw *et al.* 2011, Panter 2012). However, these governing bodies are relatively new stakeholders in flooding and catchment management, and have emerged in response to events and the changing policy landscape. For example, Lead Local Flood Authorities (LLFAs) emerged as a direct consequence of the July 2007 floods and the Pitt review 2008, advocating more localised FRM under recommendations 14 and 15, encouraging localised governance and ownership of flood risk to "positively tackle local problems" (Pitt 2008. 28), discussed further in Section 2.3.2.

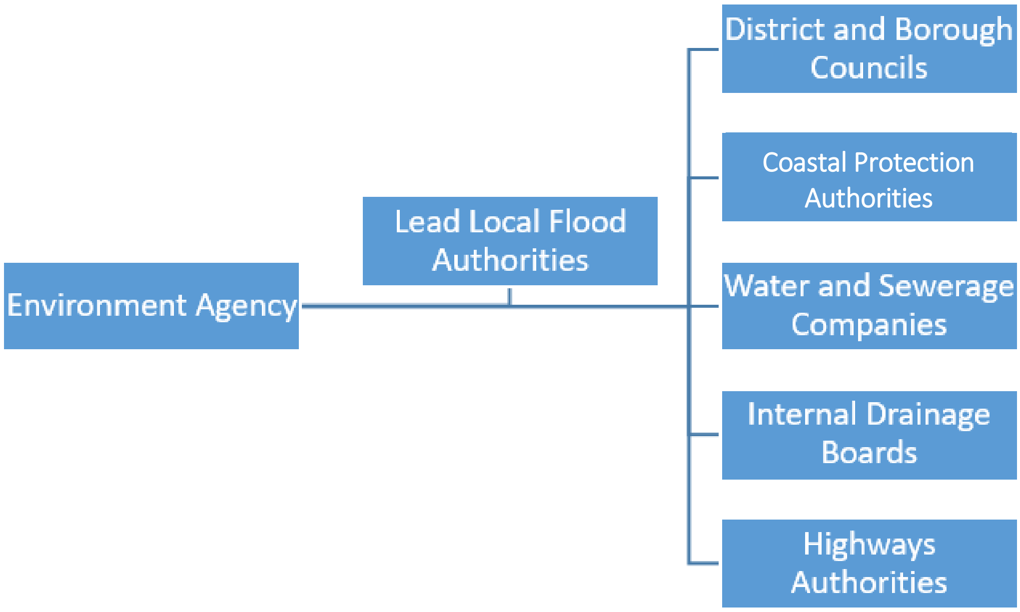

Figure 2.8 Statutory flood risk management authorities and public bodies

The Department for Environment, Food and Rural Affairs (Defra) is the lead policy making body for FRM in England and Wales. Flood risk, land-use and planning policies are developed and amended with other governmental departments, including; the Treasury (for financial approval), the Cabinet Office (for emergency management and response planning) and the Department for Communities and Local Government (DCLG) (for wider planning and land-use considerations). Risk Management Authorities (RMAs) (outlined in figure 2.8) are then tasked with delivering these national policies, who under the Flood and Water Management Act (FWMA 2010) are obligated to co-operate in order to meet the National Flood and Coastal Erosion Risk Management (NFCERM) strategy for England (Environment Agency 2016, in press) and the Local Flood Risk Management Strategies (LFRMS) developed more regionally by LLFAs. The strategic overview of every source of flood risk is delivered by the Environment Agency (as defined in the FWMA 2010). The Environment Agency is also responsible for FCERM activities on designated main rivers and shorelines, and in an incident capacity working with the Met Office to provide a flood forecasting service. LLFAs are unitary authorities or county councils that manage flood risk from localised sources, including pluvial and ordinary (smaller) watercourses. LLFAs manage risk locally with the generation and implementation of surface water management plans (SWMPs) and LFRMS.

Whilst Figure 2.8 indicates a hierarchal approach of established bodies to collectively undertake FRM responsibilities, the evolution of FRM has been incrementally reactive to the catalytic drivers of high profile, large events (Tunstall *et al.* 2009). The nuances of transition to FRM have received a considerable amount of research interest (see in particular Tunstall *et al*. 2009, Sayers *et al.* 2002, Brown and Damery, 2002). Tunstall *et al*. (2009) provides a summary of changes in flood risk and policy changes since the last century presented in Table 2.3, highlighting the paradigm shift from land drainage and rural intensification to FRM and CFMPs. This shift in ethos to manage flood risk more holistically, considering the collective management of risk as opposed to reliance on ever larger hard-engineered flood walls and levees, is something developed in response to events such as the UK winter 2015/16 storms affecting much of Cumbria and Scotland (Szönyi *et al.* 2015).

Table 2.3 Phases and drivers of UK FRM (adapted from Tunstall et al. 2009).

1940s 1970s	**Land Drainage**	Non-strategic structural engineering schemes, with focus on rural and drainage and defence orientated towards protection of crops
1980s 1990s	**Flood Defence**	Shift away from rural protection to urban flood defences, technocratic systems still dominate but increasing public attention to wider environmental and social issues.
1990s Present	**Flood Risk Management**	Transition to a more strategic, integrated system with more account of environmental and social impacts of flood risk activities. Increasing emphasis on improving resilience and partnership management of risk.

The increasing emphasis on resilience in RMAs has recognised the inability to protect all 2.4 million homes and business at risk of flooding (Environment Agency 2012a, Sayers *et al.* 2015). Therefore, FRM has evolved from a fundamentally technocentric arrangement to a be more 'sociotechnical' (Twigger-Ross and Colbourne 2009), with a noticeable shift in responsibility as society takes greater ownership of the collective management of risk, driven in part by European policies (Water Framework Directive 2000, Aarhus Convention 2001, EU Floods Directive 2007), but also by changes in governance across diverse domains of public policy (Begg *et al.* 2015, Royal HaskoningDHV 2013).

This change in governance is commonly referred to as localism (Orr 2005), a means of transferring responsibility of the management of flood risk away from central government (Defra and Environment Agency), and devolving ownership of risk towards the local level; including households, riparian land owners and communities (Coates 2015, Cinderby *et al.* 2014).

The initial dialog of the association concerning forecast increases in flood defence expenditure and climate change impacts emphasises the importance of climate change as a motivator for FRM changes, outlined in Section 2.2. Whilst there is a body of evidence that highlights society does not ineludibly link increasing flood risk and climate change (Whitmarsh 2008), the NFCERM strategy for England reflects on the need to 'manage the ever increasing risks and reduce impacts on communities', as it is 'not possible to prevent all forms flooding' (Environment Agency 2010).

Acknowledging that flood risk cannot be entirely removed raises questions regarding how to address residual risk to a more frequent hazard without building defences to all receptors affected. Based on the premise engineered structural resolutions are unfeasible for many, flood warning, behavioural change and wider risk management approaches that utilise engagement practices. Johnson *et al.* (2005) and Tunstall *et al.* (2005) acknowledged that the incremental evolution of FRM policies can be accelerated by flood events (referred to as environmental drivers by Kingdon (2003)). Elsewhere, Birkland (1998) identifies a similar pattern, emphasising the influence of major flood events as 'focusing events', which mobilize interest groups and shift the policy agenda. The 1998 Easter floods are generally demonstrative of this principle; after the Environment Agency faced public criticism to its response, Bye and Horner (1998) suggested the need for further societal engagement in FRM activities, explicitly highlighting the flood warning services, leading to the formation of the National Flood Warning Centre in 1999. Subsequently, the Environment Agency began to be less reliant on traditional flood defence construction and asset management, and transition towards a more sociotechnical risk management mosaic that stressed the importance of flood defences alongside increased communication of flood warnings and awareness raising (Johnson *et al.* 2005).

Similarly the Pitt review (2008) identified 92 recommendations after the July 2007 floods, and FRM has acted on many of them, including recommendations 14 and 15 whereby local authorities lead on LFRM with LLFAs acting positively to tackle local flooding problems. Recommendation 24 also encourages communities to participate in LFRM, enabling bottom-up management of risk as opposed to centralised governance (Edelenbos *et al.* 2017, Marshall *et al.* 2010). Whilst the 'civic model' has been advocated nationally (Nye 2011, Cook *et al.* 2016) there is still considered to be a dissociation between key local stakeholders and the RMAs with a 'top-down' approach (Twigger-Ross *et al.* 2015). An applied example of local governance in catchment management practices includes the integrated local delivery (ILD) framework, in which the lowest appropriate National and European administrative structures with an interest in the area are actively involved, whilst also seeking to strongly value the knowledge and associated role the farming community (Short, Griffiths and Phelps 2011). Unlike technocentric approaches, ILD seeks to gain local knowledge from key stakeholders, and avoids predetermining resolutions for complex problems, like flood risk. Wilcox (2013) refers to this local level of management for flood risk decision-making as a form of empowerment through effective communication and engagement. Based on LFRM activities, Daly *et al.* (2015) rank the varying degrees of engagement in Table 2.4, adapting Arnstein's (1969) 'ladder of participation' for a flood risk context.

Table 2.4 Degrees of LFRM communication and engagement (adapted from Daly et al. 2015)

Degrees of engagement	**Inform**	Telling stakeholders LFRM actions taken
	Consult	Gathering information on LFRM, listening to feedback
	Involve	Involving stakeholders in sharing ideas and discussing LFRM opportunities
	Collaborate	Partnership approach, sharing LFRM decision-making
	Empower	Local ownership with a community-led approach to LFRM

Another Pitt (2008) recommendation, considered to be largely unacted upon is number 27, where partners were encouraged to achieve greater working with natural processes (WwNP), utilising CFMPs to holistically manage risk to different scenarios and land types. WwNP is considered the protection, restoration and emulation of the natural regulatory functions of catchments, rivers, floodplains and coasts (Hankin *et al.* 2017; Environment Agency 2010). With the implications of climate change and the drive for building resilience, it is recognised society cannot rely on ever taller defensive engineering practices that were much of the focus during the 1980s – 1990s (see Table 2.2, Tunstall *et al.* 2004). More sustainable 'soft-engineered' approaches must be considered. This is reflected in a host of policies and government responses to events outlined in Figure 2.9, including Making Space for Water (Defra 2004a) – which advices that any form of sustainable development must crucially consider FCERM at the core of any decisions and activities, seeking to meet multiple objectives and policy goals with every activity. More detail on how WwNP manifests on the ground through different forms of structures and measures is provided in Section 2.5, including hydrological parameters of catchment systems and flooding processes this measure must address are discussed in Section 2.4.

	Legislative Drivers	Strategies and Agendas	Flood Events
Present	Flood and Water Management Act (2010)	Synergies Project (2014)	**November, December and January 2015-16** Northern UK, Northern Ireland and Wales
	Flood Directive (2007/60/EC)	Woodland for Water (2012)	**December 2013-14** Extensive across England, Wales and Northern Ireland
	European Eel Regulation (2007/60/EC)	UK Flood and Coastal Erosion Risk Management R&D Strategy (2012)	**April 2012** Western England and Wales
Reversed chronological order	Natural Environment and Rural Communities Act (2006)	Natural Environment White Paper (2012)	**November 2009** Cumbria
	Water Framework Directive (2000/60/EC)	Flood and Coastal Erosion Risk Management Strategy for England (2011)	**July 2007** Extensive across England and Wales
	Environment Act (1995)	Biodiversity 2020 (2010)	**December and January 2000-01** Extensive across UK
	Habitats Directive (1992)	Making Space for Nature (2010)	**April 1998** Eastern England
	Wildlife and Countryside Act (1982)	Pitt Review (2008: Recommendation 27)	**April 1953** Eastern England and Scotland
1947	Birds Directive (1973/60/EC)	Making Space for Water (2004)	**March 1947** Extensive across England

Figure 2.9 International and national WwNP drivers, including legislation, strategies/agendas and notable flood events, highlighting the relationship between events, governmental and inter-governmental legislation and strategies

2.3.2 Working with Natural Processes and Local People

This section will discuss the limited literature around LFRM engagement and public-focussed decision-making (Hopkins and Warburton 2015), specifically engagement and communication with NFRM schemes. The latest status of NFRM evidence was published in October 2017 (Environment Agency 2017a) and recognised a gap in empirically determining the performance of NFRM at different hydrological scales (especially the large catchment scales) to multiple flood risk scenarios, along with quantifying the other benefits, including water quality improvements, habitat provision and biodiversity gains (Iacob *et al.* 2012). Due to the need for quantifying performance, published research has largely focussed on modelling and gathering evidence on the effectiveness of techniques (Dixon *et al.* 2016). However, there has been limited research into communication and stakeholder engagement for NFRM, specifically the methods of collaboration with farmers and landowners in order to overcome barriers to implementation (Holstead *et al.* 2017).

Achieving early engagement with stakeholders is widely recognised as a starting point for LFRM schemes (Speller 2005, Cornell 2006). With regards to NFRM this is arguably even more critical as many of the areas where schemes could be applied are working landscapes for farmers and land managers, so require a great deal of sensitivity when selecting what could be applied, and where, to slow, store, filter and disconnect flood flows (Waylean *et al.* 2018, Forbes *et al.* 2016: 59). The WwNP evidence review (Burgess-Gamble *et al.* 2017) identified the process of engaging these stakeholders and communities at an early stage as a key research gap, recognising a lack of engagement as limiting the ability to identify options and collaboratively agree solutions. In terms of legislation, both the Floods Directive (2007) and Water Framework Directive (WFD) (2000) encourage early engagement and public participation for active involvement of concerned stakeholders. Albrecht (2016) identifies the WFD as more specific and far reaching than the Floods Directive, with article 14 of the WFD requiring consultation for the production and procedures of River Basin Management Plans (RBMPs), with the identification of solutions at early stages in the planning process. In comparison, Article 10 of the Floods Directive includes more general provisions for access to flood risk assessments (FRAs), plans and maps but has no specific provision for public comment in the early stages of planning. Schedule 7 of the FWMA (2010) outlines the NFCERM strategy (England) must consult the public on FRM strategies, and under Schedule 9, the LFRMs require LLFAs to consult RMAs and the public.

Whilst engagement in FRM seems a relatively new practice (Evers *et al.* 2016), it has been widely discussed in other areas of environmental management, including catchment management (Whitman *et al.* 2015, Blackstock *et al.* 2012, Cook *et al.* 2012), diffuse agricultural pollution (Blackstock *et al.* 2010), and soil science (Ingram *et al.* 2016). These areas encourage early and wide-spread stakeholder engagement in the design process to achieve high quality decisions, incorporating local knowledge and values (Reed *et al.* 2014, Richards *et al.* 2017, Sterling *et al.* 2017, Ball 2008). This recent shift in culture from knowledge transfer to co-production of knowledge is considered the most effective form of generating open dialogue, building trust and sustaining motivation (Fazey *et al.* 2014). Table 2.4, Section 2.3 identifies the need for a more extensive form of communication and engagement within FRM (Daly *et al.* 2015). Lane *et al.* (2015) and Callon (1999) outline three distinct models to involve stakeholders in FRM decision-making:

1) *Educating the public* - assuming there is a difference in understanding of flooding between 'experts' and 'lay' people, requiring top-down communication methods and intermediaries to relay complex hydrological processes to the public (Godfray *et al.* 2014, McEwen *et al.* 2015). This approach maintains a 'hierarchy of information' and lack of knowledge sharing (Johnson *et al.* 2007), an increasingly unpopular method of engagement in modern FRM practices (Defra 2009b, Efra 2016), and an increasingly unfeasible method of obtaining landowner and farmer support in installing NFRM interventions (O'Connell *et al.* 2010, Hankin *et al.* 2017b).

2) *Debating the public* - developed by Callon (1999), it is emphasised that those who have a stake in the decisions made should be empowered to directly question 'expert' knowledge, enabling farmers and landowners to argue the validity of scientific findings and increasing the legitimacy of the decision-making process amongst stakeholders (Evans 2015). A classic example is the opening of LFRMs and

CFMPs to public consultation. The consultation exercise enables agencies to formally take on board public knowledge, however, concerns regarding complexities in data and how ‘experts’ have calculated results (especially models) often leads to a lack of trust between the consultees (public) and agencies (experts) (White and Richards 2010).

3) *Active engagement* - allows for a transfer of experiences and understanding (technical and local) to co-produce knowledge, enabling engagement to become a much earlier part of the research and wider environmental management framework (Leadoux *et al.* 2003). The co-production of knowledge, commonly referred to as Participatory Action Research (Kindon *et al.* 2007), allows stakeholders to inform the decision-making process as opposed to scrutinising and debating findings when presented. Collins and Evans (2002) recognise that flood risk understanding can be influenced by experience-based expertise, informed by flood memories of how land and rivers responds to heavy rainfall (McEwen *et al.* 2012, Krauss 2012). Unlike passive engagement, active engagement ensures continued discussion from both a local and technical understanding and recognises the importance of place-based knowledge (Lane *et al.* 2015).

Wilkinson *et al.* (2014) recognised that active engagement to co-produce knowledge is crucial to enable effective catchment management plans designed to meet stakeholders’ aims, such as flood risk reduction, water quality improvement, habitat provision, biodiversity benefits and amenity gains. Wilkinson refers to this as the catchment systems approach (outlined in Figure 2.10), used to endorse the integration of local knowledge and stakeholder engagement in runoff management schemes, from identification of the problem through to implementation of a solution.

Figure 2.10 The Catchment Systems Engineering (CSE) Approach (Wilkinson *et al.* 2014)

With regards to agricultural land management and flood risk, Hewett *et al.* (2008) developed the Floods and Agricultural Risk Matrix (FARM) tool in order to assist engagement with farmers and landowners, who are considered the most critical stakeholders in NFRM decision-making due to the importance of their support for delivery, as well as their local knowledge in identifying suitable opportunities (Morris *et al.* 2010). The FARM tool is used as a decision support matrix (DSM) to assist the assessment of flood risk sources and pathways from agricultural land, and to enable stakeholders to explore possible mitigation strategies (see Figure 2.11).

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Figure 2.11 The Floods and Agricultural Risk Matrix (FARM) Tool (Morris *et al.* 2010)

Posthumus *et al.* (2008) used the FARM tool in the Rivers Laver and Skell catchments, Yorkshire, during a workshop conducted as an open focus group. Whilst runoff attenuation that temporality stored flood water was found to have flood risk gains, participating stakeholder farmers thought this was outside their obligation of 'good farming practice'. Therefore, in the course of the workshop, all participants agreed that effective and targeted engagement methods (in addition to proportionate funding), in which scheme planning and design were needed to successfully involve farmers in LFRM.

A similar, actively engaging catchment management programme seeking to address flooding and pollution issues was the Aquarius project, consisting of 15 partners across six countries and seven catchments (see Figure 2.12). All schemes adopted a 'bottom-up', local governance approach with farmers as the water managers (Wiborg *et al.* 2011). The projects utilised the farmers' local knowledge and established networks to address place specific problems, including areas of high soil runoff, as well as identifying further research gaps from farmers, including the need to better understand mitigations strategies.

Figure 2.12 Aquarius catchment projects across seven catchment sites (Wiborg et al. 2011)

The Tarland catchment pilot, also known as the Tarland Burn Flood Alleviation Study (TBFAS), covers 72km² and is located in Aberdeenshire, Scotland. The Tarland catchment comprises the main river itself along with upstream tributaries draining the upstream hills. The land cover includes farmland, upland moorland, conifer plantation, semi-natural broad leaved woodland and urban areas that face frequent and flashy flooding. The Aquarius project worked closely with land managers to establish NFRM measures. By using project facilitators, the scheme identified the importance of building good relationships through an open dialogue of catchment and land use characteristics, and the ability to generate large cumulative levels of upstream storage through minimal loss of productive agricultural land. However, considerable complexities were found when trying to engage farmers:

- The changeable nature of cadastral land boundaries, ownership and tenancy models create legal complications when designing long-term flood alleviation measures, requiring careful engagement to identify key stakeholders (NFU 2016, IVB North Sea Programme 2011).
- Due to changeable market forces, land managers were tentative when agreeing long-term changes to land use established on the current funding landscapes for crops and payments for public goods (Forbes *et al.* 2016). Changes in policy, markets and funding regimes could make land with permanent NFRM measures less flexible to generate profits.
- Land managers were nervous about the unpredictability of when land will be flooded and the potential impact on crops or grazing. Therefore, it is important for farmers and landowners be involved with the design of a scheme in order to be fully aware of the impact of WwNP measures. In order to successfully co-design measures, the project facilitators also recommended a clear and shared definition of NFRM as this was found to differ across projects and between farmers, leading to confusion of NFRM characteristics and the scheme's aim (Dee Catchment Partnership 2014).

Similar challenges have been met and overcome in the other Aquarius projects (IVB North Sea Programme 2011) and across wider literature examining the barriers of NFRM (Sniffer 2011, Holstead *et al.* 2016, Spray *et al.* 2016, Waylean *et al.* 2017, McLean *et al.* 2015). Holstead *et al.* (2016) generated a diagrammatic overview of the challenges based on experiences in Scotland (see Figure 2.13). These factors were identified as the key causes for poor NFRM uptake in Scotland, with WwNP at the forefront of Scottish national flood risk policy, including Water Environment and Water Services (Scotland) Act 2003 and the Flood Risk Management (Scotland) Act 2009.

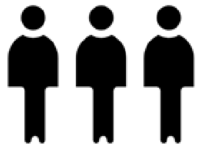
Factors that influence farmer's decisions on NFRM implementation			
Economics	**Policy**	**Social**	**Physical**
			
Local: Costs, financial incentives, marks, labour economies of scale **Macro:** Funding and organisations to assist with paperwork, complexity of process, time, standing of key organisations	**Local:** Availability of support with appropriate information and trusted advice, legal assistance if anything goes wrong **Macro:** Complementarity with other policies, need to get involved.	**Local:** Personal interests, skills and experience in WwNP drainage practices **Macro:** Social networks, what neighbouring farmers think of NFRM, presence of local 'champions'.	**Local:** Size, ownership, business structure, soil type, weather. Possible pests and parasites with holding more water on the landscape. **Macro:** Catchment plan required, including urban area involvement

Figure 2.13 Factors that influence Scottish farmer's' decision-making on implementation of NFRM measures (adapted from Holstead *et al.* 2016). These factors are categorised into four distinct (but interlinked) groups, including: economics, policy, social and physical. Further consideration of local (site based) and macro (catchment, regional, national and international) scales are also provided.

Waylean *et al.* (2017) identified the need for an intermediary approach that could work across farms and sub-catchments in a larger catchment management programme. SEPAs Natural Flood Management handbook (Forbes *et al.* 2016: 79) considers conceptual tools and early engagement practices helpful to enable the identification of opportunities at the site scale, however, a lack of a consistent and transparent methodologies prevents replicability (Rivers Trust 2016, White *et al.* 2010).

The River Tone and Parrett catchment in Somerset, England, the South West Farming and Wildlife Group (FWAG) are undertaking 'passive engagement' that leaves all decision-making to identify opportunities with farmers and landowners, entirely reliant on these stakeholders designing a scheme and bidding for funding for its implementation under the *NaturEtrade NFM* programme (Somerset Rivers Authority in press). Results of the participation numbers and opportunities identified have not been released, but this form of engagement is considered less proactive than those utilising a facilitator, local engagement and available evidence (Orr *et al.* 2015).

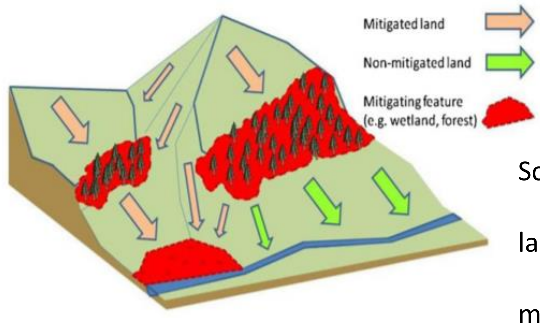
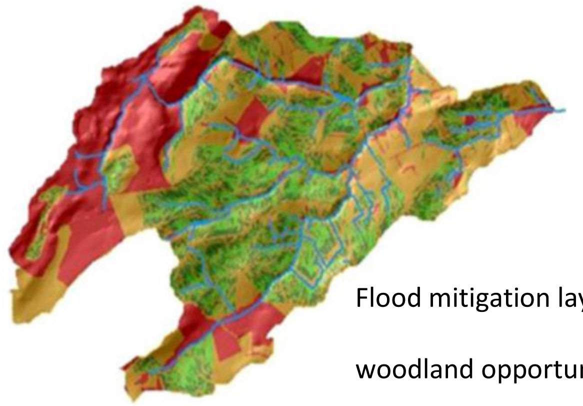
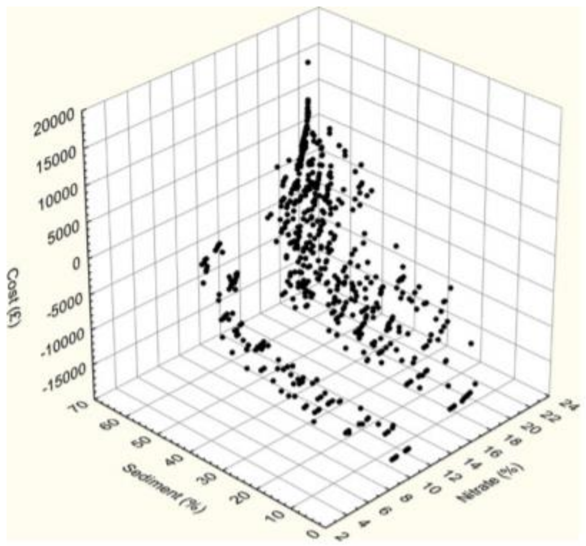
Effectively engaging farmers in environmental management has become an important research focus since the Aarhus convention (2000), including research into persuasion theories and knowledge transfer approaches, which found that before farmers will consider solutions, farmers need to believe they are not the singular cause of a problem (e.g. downstream flood risk) (Blackstock *et al.* 2010, Frontier Economics 2013). Effective engagement is also highly dependent on the recognition of the various farm types, businesses and individuals, with a variety of approaches and tailored advice required to engage them, including facilitators for specific advice (Mills *et al.* 2017, Holstead *et al.* 2015).

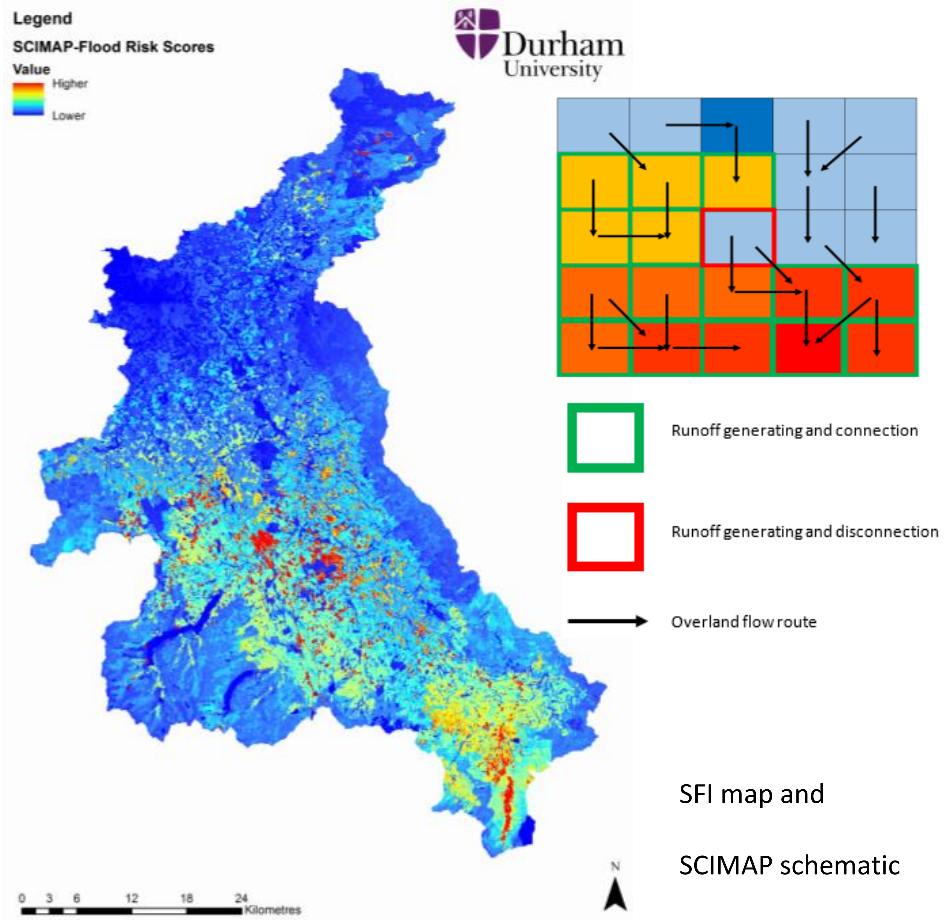
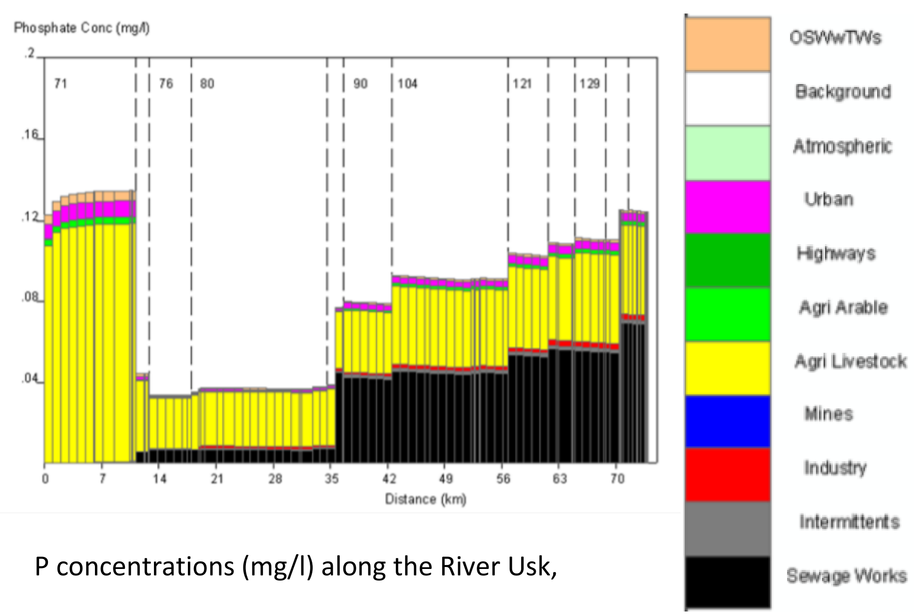
To gain and maintain stakeholder support for an NFRM approach, the effective communication of science is vital (Waylen *et al*. 2017, O'Connell and O'Donnell 2014). To be effective, any communication of flood risk science needs to be salient (relevant to the context), credible (accurate and unbiased) and legitimate (transparent and useable) (Grainger, Mao and Buytaert, 2016, Ingram *et al*. 2016, Blackstock *et al*. 2010, Cornell 2006). Trade-offs may arise in trying to achieve these outcomes and often involve an iterative engagement process (Hankin *et al.* 2017b); however, continued interaction may be to the detriment of credibility as it can expose uncertainties in the science, raise the expectation of participants and be affected by perceptions and bias (Chess and Purcell 1999, Derrick 2009, Ingram *et al*. 2016). The effective engagement of stakeholders may be limited not only by the credibility, salience and legitimacy of the scientific data, but also by the methods of delivery, including the tools used to support the engagement process. Cook *et al*. (2012) suggested that closing the gaps in knowledge was restricted by the availability of data, use of technology and lack of effort. Communicating complex spatial and environmental information is challenging and must also consider political and social values (Smith, Wall and Blackstock 2013).

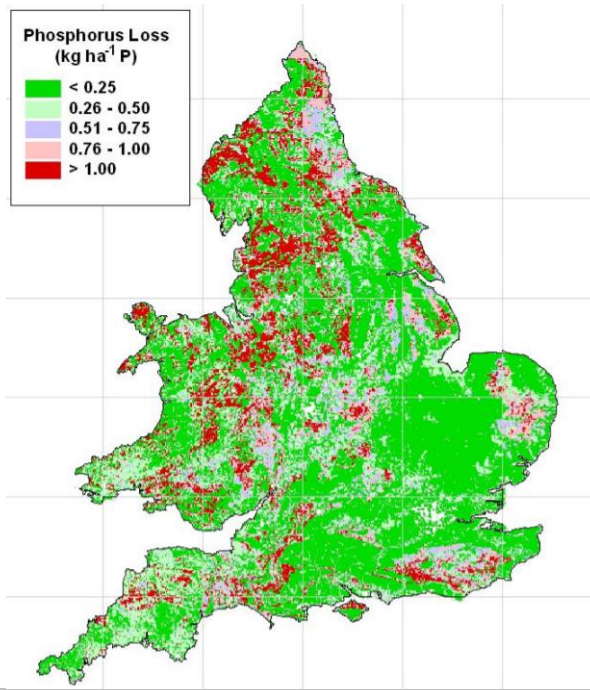
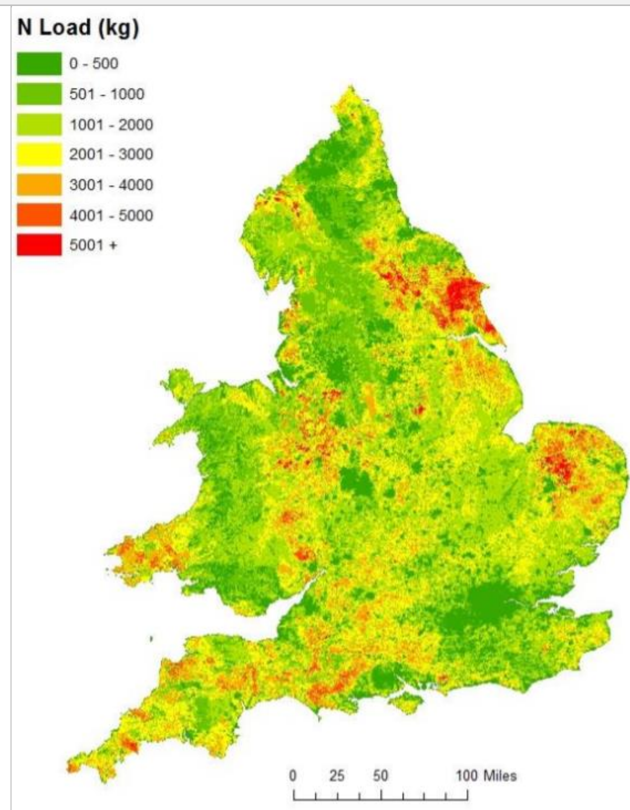
The benefits of co-designed and community-led LFRM, including NFRM, is well reported (Short *et al.* 2016; Environment Agency 2016; Yorkshire Dales 2016). The Pontbren farmer-led scheme in South Wales (Jackson *et al.* 2008; Marshall *et al.* 2009) enabled the local farming community to develop local schemes to work with natural processes for soil improvement through the planting of tree shelter belts. McLean *et al.* (2015) recognise this community-led scheme as a method of 'learning from key stakeholders' by firstly identifying possible options for flood risk reduction, and secondly by facilitating the implementation (Fitton *et al.* 2015). Examples include the Earlston in Eddleston Water sub-catchment and Wooler sub-catchment of the Tweed, Scotland, that utilised facilitators to work with farmers to address agricultural runoff and diffuse pollution (Bracken *et al.* 2016); and the Dutch 'room for the river' programme that has recommended authorities' work with upstream farmers (PKKR 2006). Table 2.5 provides an overview of engagement tools used most commonly in environmental management to address diffuse agricultural pollution, as well as some that have been tailored to consider LFRM strategies, including NFRM and WwNP. Whilst each tool is varied based on its components and method of application, they collectively recognise the importance of incorporating local knowledge, but differ on stages of local knowledge attainment and incorporation in catchment management via problem identification and solution building (Environment Agency 2014, Frew 2009, Todorovici *et al* 2008, Harmonicop 2005, Tapsell *et al.* 2006, Sorensen *et al.* 2006, Wilcox 1994).

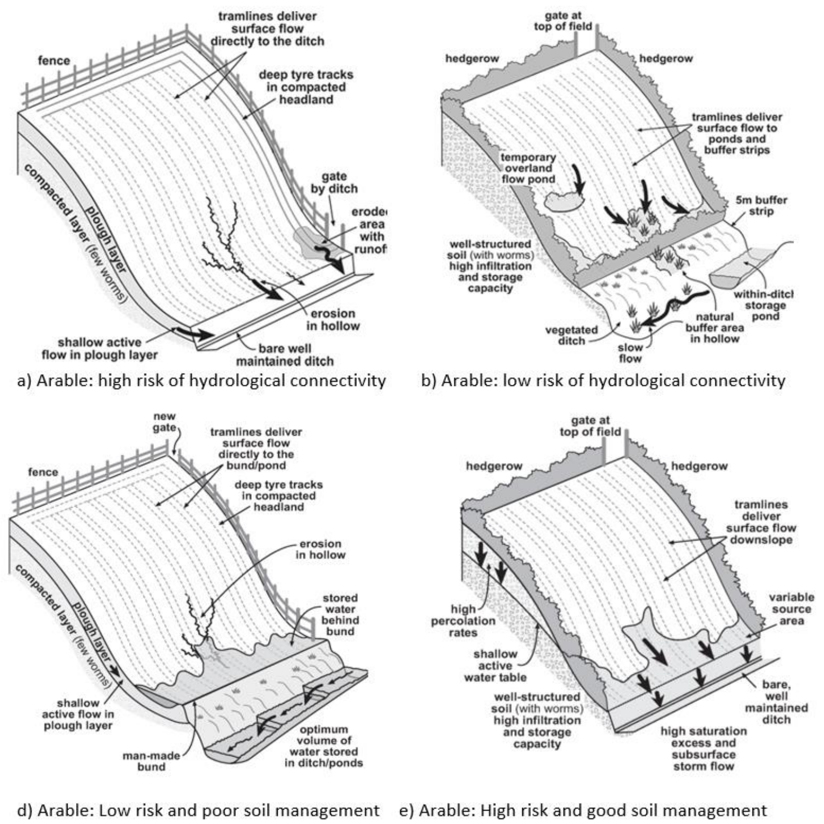
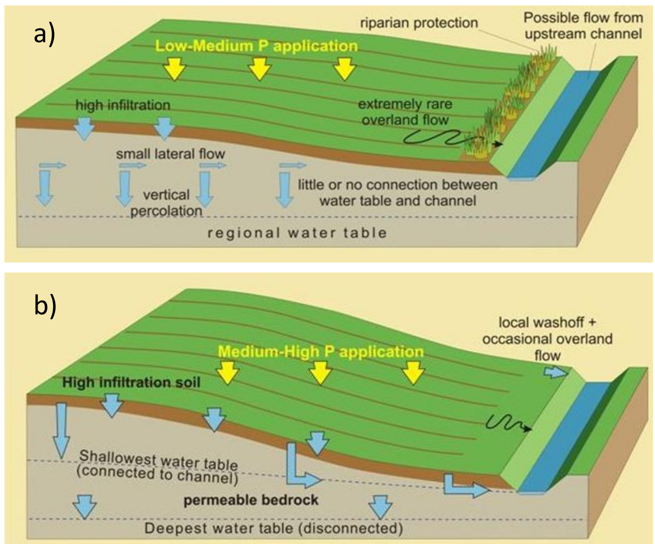
2.3.3 A Review of Multi-Disciplinary Engagement Tools for WwNP

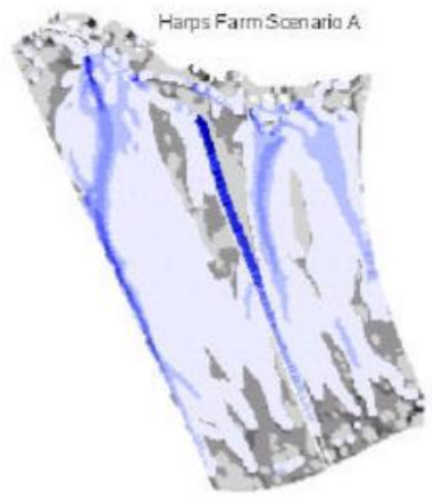
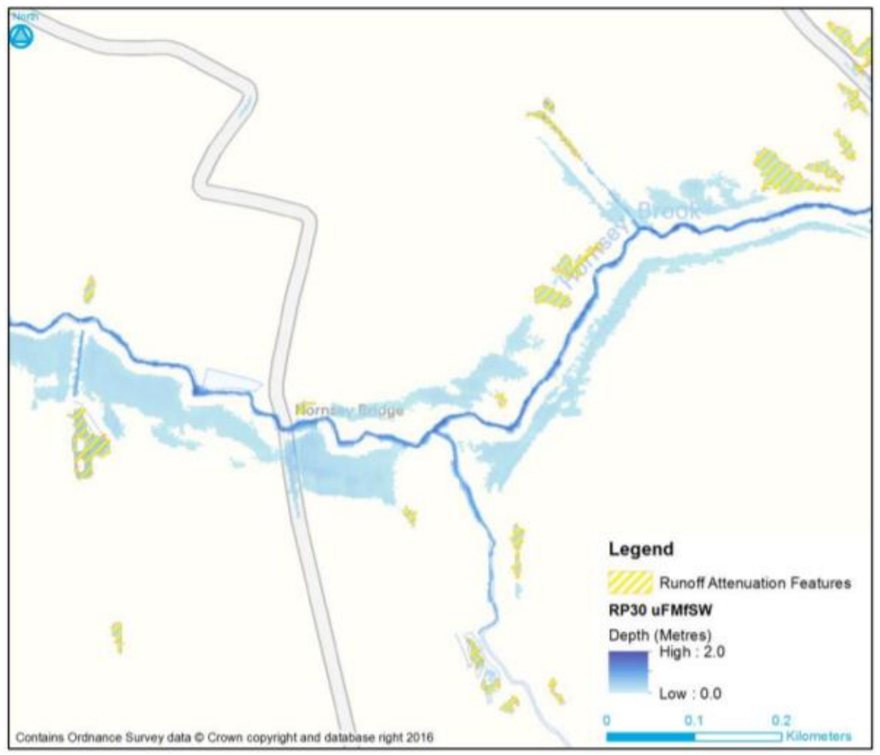
Table 2.5 Engagement tools used to participate farmers in a CaBA. Multi-disciplinary tools are discussed in relation to their ability to represent opportunities for WwNP principles to address hydrological connectivity and flood risk.

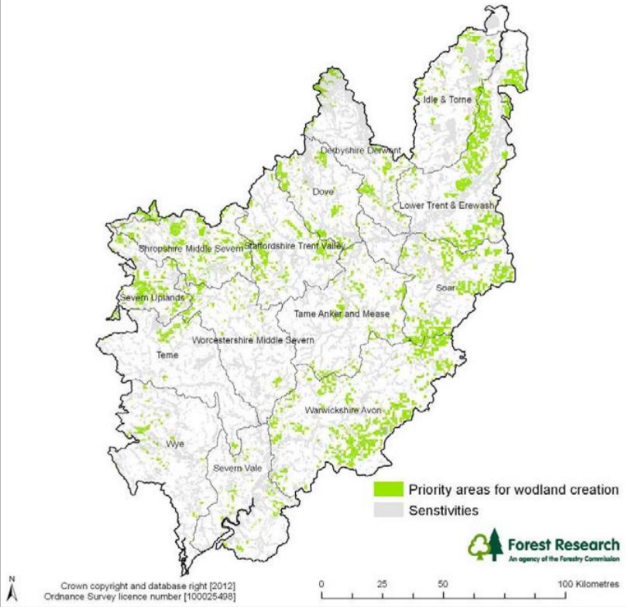
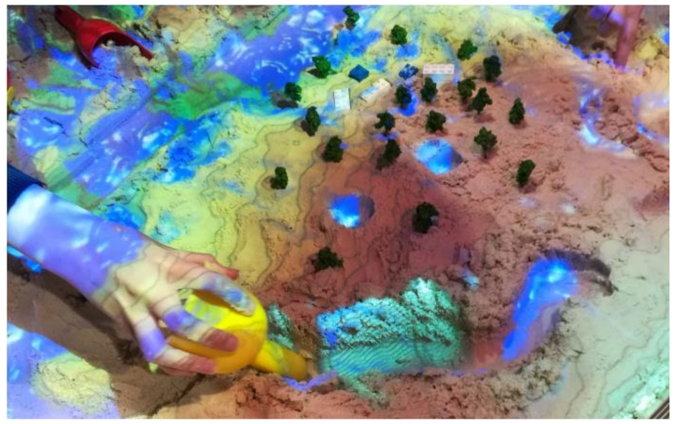
Functionality and Data	**Description**	**Application**	**Schematics and example outputs**
1. Polyscape (Jackson *et al.* 2008, Jackson *et al.* 2013, Pagella 2011)			
GIS Framework - Digital elevation; Land cover; Soil type	Designed to explore compromises and co-operation across ecosystem-services in land management (field to meso catchment-scale). Polyscape includes algorithms to identify the influence of changing land cover on flooding, provision of habitat, connectivity of habitat, erosion, diffuse pollution, carbon storage and productivity. Changes in land use can be input into the tool and "red, amber and green" coded effects produced as maps, allowing visualisation of any scenarios. Polyscape offers a means of flood risk prioritisation, regardless of event magnitude, where the tool corrects flow accumulation by removing any flow that accumulates in "sinks" within the elevation model. These sink areas within the elevation model are considered low priority for flood risk as mitigation (albeit not tested) already exists.	Pontbren, Mid-Wales (12.5km^2): High priority areas for afforestation are those where unmitigated high flow accumulation is concentrated. Grassland with > 500 m^2 non-mitigated contributing area are considered a priority and shown in light green; moderate flow routes (125–500 m^2) are shown in dark green; areas with insignificant flow (<125 m^2 contribution) are shown as orange; and areas that are providing flow mitigation (e.g., trees, ponds, deep soils with a high capacity for infiltration, or other flow sinks) are shown as red.	 Schematic of delineated landscape; mitigated and non-mitigated areas  Flood mitigation layer for broadleaved woodland opportunities across Pontbren
2. Farm Scale Optimisation of Pollutant Emission Reductions (FARMSCOPER) (Gooday and Anthoney 2010, Gooday *et al.* 2014, Zhana *et al.* 2012)			
Decision Support Tool - SAAR; Soil type; Rural land registry	Farmscoper is a decision support tool (DST) used to assess diffuse agricultural pollution sources and loads on a farm, and provide a high level quantification of intervening to mitigate. The tool can adapt the representation of farms to reflect land use and environmental factors. The tool contains > 100 mitigation techniques, based mainly on Newell-Price *et al.* (2009) Mitigation Method User Guide.	Hampshire-Avon, UK (~1700 km^2): A collection of representative farm types and physical characteristics were generated. Farmscoper outputs recommended that decreases in P and SS loads in response to mitigation methods are minor (e.g. 10% for P). These outputs were designed to target engagement activities, however, no engagement has been undertaken (to date).	 Cost-effective mitigation methods determined for a mixed farm in Hampshire-Avon

3. **Sensitive Catchment Integrated Modelling Platform (SCIMAP) (Reaney *et al.* 2013, Reaney *et al.* 2018, Reaney and Pearson 2018, Walker *et al.* 2017)**			
GIS Risk Mapping Framework - SAAR; digital elevation; land cover	SCIMAP is designed to identify source of diffuse pollution across the landscape (known as critical source areas), assessing the catchment in terms of hydrological connectivity from sources (fields) → pathways (rills, gullies and ditches) → receptors (receiving watercourses). Like Polyscape (Table 2.5, 1) hydrological connectivity is only recognised to be a problem when flows (often laden with pollutants) connect to a receiving watercourse. The outputs do not provide empirical predictions in real world units (e.g. mg l^{-1}) but instead makes a relative assessment across the catchment of interest to identify probably sources and pathways. With regards to NFRM and CBFM, SCIMAP-Flood disregards sources and pathways that are intercepted by "sinks" in the data elevation model (DEM), as those fields and subsequent flow pathways are not an issue to downstream flood risk.	Willow Brook, UK, Trent Rivers Trust (~50km^2): in an effort to engage communities of farmers on catchment management issues, including diffuse pollution, river health and flood risk, SCIMAP was used to provide Surface Flow Index (SFI) maps in order to educate farmers on the areas with a high propensity to connect to receiving watercourses. The maps were found by farmers to be engaging and non-technical (Walker *et al.* 2017). Whilst farmers did not agree with all the outputs and found the 5m^2 too coarse in sensitive locations (e.g. converging flow pathways), it was a sufficient baseline to initiate a conversation based on evidenced understanding.	 SFI map and SCIMAP schematic
4. **The Source Apportionment-GIS (SAGIS) Tool (UKWIR 2012, Constantino *et al.* 2015, Rivers Trust 2017)**			
GIS Modelling Framework - WFD sources; SIMCAT software	Developed to support river basin scale planning of water quality improvement, SAGIS is a GIS map based tool to apportion loads and concentration of chemicals to WFD water bodies. The tool aims to identify effective programmes of measures, whilst maintaining the 'polluter pays principle', thus ensuring a fair proportioning of responsibility for improving water quality across all responsible sectors. The model accounts for point and diffuse sources including industrial discharges, waste water discharges, combined sewer outfalls, mine waters, storm tank discharges, livestock inputs, arable runoff and urban runoff.	Dŵr Cymru Welsh Water (DCWW): whilst not a FRM tool, SAGIS was able to identify changing concentrations of pollution in order to trace the pathways to sources. Graphical outputs show phosphate in mg/l against distance from the headwater, plotted against WFD classification boundaries. The tool has not been applied to farmers, but used to engage regulatory authorities (e.g. water companies and Environment Agency).	 P concentrations (mg/l) along the River Usk, including apportionment to potential sources in key

5. **Phosphorus and Sediment Yield Characterisation In Catchments (PSYCHIC) Tool (Withers *et al.* 2002, Collins *et al.* 2007, Strömqvist *et al.* 2008, Davison *et al.* 2008)**			
GIS Modelling Framework **-** **Digital elevation; soil type; land cover; WFD sources**	A process-based mode assessing the mobilisation of P and SS in runoff and delivery to receiving watercourses. This includes representing pathways that release desorbable soil P and SS via surface pathways. This tool works at multiple hydrological scales, and can differentiate a number of arable and livestock decisions regarding husbandry, as well as to other influences such as slope and soil class.	Der inwent-Cocker, Cumbria, England (626km^2): the PSYCHIC tool modelled total P/yr from the Derwent-Cocker catchment at 1.2 kg ha−1 year−1, highlighting the importance of P application rates, soil classes and the increased connectivity provided by assisted drainage in determining pollution 'hotspots'. The tool is currently being used to engage stakeholders and devise abatement strategies, including buffer zones and improved soil husbandry.	 Annual average total P loss from diffuse agricultural sources (1970-2014), expressed per hectare of all agricultural land
6. **NEAP-N (Anthony *et al*. 1996, Lord and Anthony 2000, Silgram *et al*. 2001, Lord *et al.* 2007, RSPB 2013, Lee *et al.* 2016)**			
GIS Modelling Framework **-** **Digital elevation; soil type; land cover; WFD sources**	A process-based model of Nitrates (NO_3) mobilisation in runoff and leaching to receiving watercourses. Devised to assess nitrate loss from agricultural land, applicable to any catchment in England and Wales. Nitrate loss potential coefficients are assigned to varying pastoral and arable categories in a 1km^2 resolution. Output of the model is total annual NO3 loss from the soil profile for agricultural land, and associated water flux. The livestock coefficients represent the short and long-term increase in nitrate leaching risk associated with livestock and spreading of manures. For grassland, nitrate leaching loss is represented mainly through the coefficients for grazing livestock, on the grounds that due to the wide variation in stocking densities, losses are much more closely correlated with stock numbers than with the area of grassland.	Poole Harbour, Dorset, England: This study has examined the feasibility of a 'nitrogen trading' Payments for Ecosystem Services (PES) scheme around Poole Harbour. An 'educating the public' approach was used with farmers to engage them around sources and risks of pollution, with varying levels of success, the principle objection being 'paying polluters'. Farmers found engagement to be insufficient in identifying measures and suitable payments structures for PES.	 Annual average total nitrates loss from diffuse agricultural sources (1970-2014), expressed per hectare of all agricultural land

7. **Floods and Agricultural Risk Matrix (FARM) Tool (Hewett *et al.* 2008, Posthumus *et al.* 2008, Nicholson *et al.* 2012, Wilkinson, Quinn and Hewett 2013)**			
Decision Support Matrix - Conceptual	A decision support matrix (DSM) intended to assist the assessment of flood risk sources and pathways from agricultural land, and enable stakeholders to explore possible mitigation strategies. The DSM covers both arable and pasture farms in order to conceptually manage the risk of i) hydrological connectivity to receiving watercourses and, ii) soil storage, infiltration and tillage regimes impact. A relative weighting method is applied to rank lower to higher runoff risk for types of farms, the end user is then able to assess numerous land-use management options (including some NFRM practices) to ameliorate runoff risk. The conceptual model applies exercises for the user to identify the hydrological connectivity from the farm before scoping Farm Integrated Runoff Management (FIRM) plans. The opportunities provided in the tool include: Hedgerows (or stone walls for pasture farms), buffer zones, wetlands, ponds and flood storage areas.	Belford, Northumberland, England (6.8km^2): the tool was applied to engage farmers and landowners, in conjunction with the Newcastle University Farm Pond Location Tool (PLOT) (not available under open license), to aid the process of locating ponds, interpolating available elevation data (LiDAR) to show opportune sites in the bottom of fields and/or in field corners. No feedback on the tool has been published, however, it has been successfully used with over 10 farmers to devise FIRM plans (Nicholson *et al.* 2012). The tool has also been trialled with farmers in the Laver and Skell catchments as part of the Ripon Multi-Objective Pilot Project, North Yorkshire.	 a) Arable: high risk of hydrological connectivity b) Arable: low risk of hydrological connectivity d) Arable: Low risk and poor soil management e) Arable: High risk and good soil management Conceptual schematics of different farms hydrological connectivity
8. **Phosphorus Export Risk Matrix (PERM) Tool (Hewett *et al*. 2004, 2010)**			
Decision Support Matrix - Conceptual	A DSM to enable farmers to assess risks of P loss from their holdings and to discover methods to reduce P losses whilst sustaining farm business income. The main aim of the tool is to enable landowners and farmers to assess the differences between their current farm practices with possible (conceptual) alternatives. The tool also indicates the risk of P reaching the regional aquifer, with hydrological connection from surface water channels and highly permeable soils and local geology. Low to medium risk is regarded as those farms with no to little lateral flow resulting in near vertical percolation (infiltration).	The PERM tool is an evolving DSM that has not been trailed beyond the local farm scale. Harps Farm, Northumberland (England) trailed the tool at two different fields within the farm. The farmer was not engaged to use the tool as an end-user, rather researchers applied to the tool at the farm to trail the tool for future engagement. The tool aided the development of field runoff management plans, also informed by observed knowledge of the fields flow pathways, crops and a fertiliser application rates.	 a) groundwater dominated system with low-medium risk of P transfer. b) groundwater dominated system with high risk of P transfer

9. **TopManage (Hewett and Quinn 2003, Hewett *et al.* 2004)**			
GIS Mapping Tool - Elevation data (LiDAR)	GIS DEM analysis tool for identifying overland flow pathways at the site scale. By using freely available data (including ditches and channels at 50cm grid cells, and wider terrain at 2m resolution), the tool is able to denote the local runoff influential factors. Also, the datasets used enables the inclusion of hedgerows, tyre-tracks, tramlines, tracks, land drains and storage features to be replicated in ArcGIS. ArcView allows the data to be represented in 3D.	Harps Farm, Northumberland, England: A field scale assessment of Harps Farm identified overland flow losses and high flow accumulation areas. This was ground truthed with the farmer who confirmed these areas convey overland flows. From the GIS tool, researchers were able to identify opportune areas to deliver overland flows into 'topographical hollows' (e.g. ponds, swales and sediment traps).	 Example flow accumulation map, dark shading indicates areas of high overland flow accumulation
10. **JBA NFM Opportunity Mapping Tool (Hankin *et al.* 2016a, JBA 2017, Hankin *et al.* 2017b, Burgess-Gamble *et al.* 2017)**			
GIS Mapping Tool - Elevation; land cover; river network; soil; risk of flooding from surface water (RoFfSW) and river and sea (RoFfR&S)	A high level (OS 1:2500) scale screening of attenuation, afforestation, floodplain reconnection and soil structure improvement. The GIS screening tool aims to support the identification and development of WwNP schemes, RAFs were identified in areas of high flow accumulation using the RoFfSW datasets. JBA Consulting also developed the JBA Runoff Attenuation Feature Finder (JRAFF) tool, which identified these opportunities based on ruling out constraints (urban areas, roads and within the channel network) and size restriction, between 100 – 5000m^3 in order to avoid exceeding storage above the Reservoir Act. Afforestation was also targeted using the Woodland for Water dataset (discussed Table 2.5, 11), to encompass three locations of afforestation including: riparian, floodplain and cross-slope areas of high SPRHOST. Floodplain reconnection potential was identified using the RoFfR&S dataset, using high risk extents in rural areas to encourage earlier connection to the floodplain. Soil structure improvement used LCM2007 data to identify opportunities 'acidic grassland or improved grassland to return to rough grassland' and total flood storage was estimated for the percentage of the catchment changed.	River Kent, Cumbria, England (LIFE-IP Project): A workshop was organised to help identify the feasibility of pre-mapped opportunities using the NFM Opportunity Mapping tool with catchment stakeholders. The workshop also aimed to build relationships in order to understand a range of issues from local flooding mechanisms to land-ownership and historical catchment knowledge. The mapped opportunities were modified considerably by attending catchment stakeholders (mostly RMAs). However, a lack of farmers led to an underrepresentation of these critical stakeholders in the opportunity mapping process. The tool was also found to not provide wider NFRM measures that could have been applicable.	 Example map of baseline surface water flooding (3.3%AEP) and opportunities for delineated runoff attenuation features (green hatched areas)

11. **Woodland for Water (WfW) Dataset (Nisbet *et al.* 2011, Broadmeadow *et al.* 2014)**			
GIS Mapping Tool - Digital elevation; soil type; RoFfSW and RoFfR&S; land cover	A strategic tool to identify opportunities for afforestation that can ameliorate diffuse pollution and flood risk. The mapped based outputs main purpose was for targeting Countryside Stewardship (CSS) areas. They identify priority sites (at a scale of 1 km^2) in catchments of poor - moderate ecological status due to diffuse pollutant loads (nitrate, phosphate, sediment, pesticides and faecal indicator organisms); RoFR&S dataset, and priority areas with high SPRHOST values attributed to rapid overland flows, and finally includes information on constraints to woodland planting including open water, urban areas, existing woodland and areas of deep peat soil.	Midlands Woodland for Water (>1000km^2): The dataset provided a high level indication of woodland opportunities across different locations of the Severn River Basin District. The dataset was informed to farmers via Natural England and the Forestry Commission for targeting the Additional Contribution payment for afforestation to deliver flood risk and water quality benefits.	 Priority areas for woodland creation across the Warwickshire-Avon, England
12. **Augmented Reality (AR) Sandbox (JBA Trust 2017, Rivers Trust 2017)**			
Physical Model - Conceptual	A physical visualisation model that demonstrates how topography affects runoff and river response in a catchment. By moulding a sand-pit that represents a DEM, users can ‘augment’ the catchment in real-time via a projector displaying the DEM values and water extents. Users are also able to simulate rainfall events and watch how the virtual runoff moved through the catchment, exploring how changes in land use affect flooding.	The sandbox has not been used to engage farmers around catchment management and NFRM, however, the JBA Trust aim to explore how NFRM concepts are visualised and assessed using the sandbox, including the impact of afforestation, storage features, and river restoration.	 AR Sandbox demonstration. Blue indicates rainfall and runoff.
13. **Tweed Forum Catchment Model (Tweed Forum 2015)**			
Physical Model - Conceptual	The physical catchment model has two downsized hypothetical river catchments– the first catchment featuring NFRM and another reflecting a more intensively management agricultural landscape. “Rain” is introduced into the catchment via a piped inflows enabling the user to visualise the movement of water through the two different catchments.	The Tweed Forum have used these physical models to demonstrate the concept of NFRM to farmers in the Tweed. Feedback has not been published.	 Miniature catchments. NFRM (left), typical (right)

The potential NFRM engagement tools reviewed in Table 2.5 describes a wide-range of sources and applications. Whilst each tool is varied based on its input components, method of application, and amount of farmer experience, some were considered to provide a greater specific spatial and conceptual output more suited for scoping NFRM opportunities. In order to better understand the spatial heterogeneous hydrological connectivity of specific farms and estates, the multiple DSTs and DSMs provide mapped output of overland sources and pathways is critiqued in this section.

NEAP-N, PSYCHIC and Polyscape provide a mapped DSM output that presents propensity of pollutant delivery on a farm scale, per ha resolution. However, these tools do not present individual sources and pathways, unlike the $5m^2$ SCIMAP resolution, which maps sources and pathways that connect to the receiving watercourse using a risk-based model. TopManage also provides mapped outputs of sources and pathways in areas of high to low risk, however, this requires a high resolution ($0.5m^2$) DTM to simulate overland flows, and is ten times more detailed than SCIMAP.

FARMSCOPER, FARM, JBA NFM Opportunity Maps, Woodland for Water dataset, AR Sandbox and the Tweed Forum physical model provide indicative NFRM opportunities in a variety of modes. The latter two provide physical models for hypothetical catchments, however, have not been tested with farmers exploring NFRM on their individual holdings. FARMSCOPER, Woodland for Water and the JBA NFM Opportunity Maps provide spatial potential of NFRM opportunities, yet, these are considered too prescriptive for a 'co-design' process. The FARM tool, unlike SCIMAP, gives a conceptual (not mapped) overview of the farmers' current hydrological connectivity but also examples of NFRM opportunities that could be applied to address overland flows and in-channel high-flows. A justification of the existing DSMs and DTMs tools used within this research are provided in more detail within the research methodology, section 3.3.1.

2.4 Defining Natural Flood Risk Management

NFRM is commonly misunderstood due to ambiguity in its definition and term of reference. Whilst NFRM is frequently referred to as 'new' and 'novel', neither are the case. Historically, NFRM principles (and even some of the methods) have been applied, normally in isolation at the field-scale, for centuries. Predating the intensification of agricultural land management, also known as the era of land drainage, the practice of holding water in the landscape for multiple functions has been well reported (Quinn 2015). Early Mesopotamia (400BC) is recognised as the first civilisation to develop irrigation systems that allowed fields to flood, replenishing nutrients and silts to the farmed environment in spate conditions when the Tigris and Euphrates burst their banks (Mumford 1961, Kenoyer and Jonathan 1998). Internationally, WwNP and NFRM have multiple nomenclature outlined in Table 2.6. Whilst these definitions vary, the principle elements of working with natural processes and landscape functions to manage sources and pathways of flooding collectively apply. These methods aim to reduce downstream flooding, whilst also ideally enhancing other potentially significant ecosystem services (aquatic, riparian and terrestrial) such as: greater biodiversity, improved soil structure, reduced diffuse pollution, carbon sequestration, reduced soil erosion, greater agricultural productivity and improved amenity (Wade and McLean 2014, Dadson *et al.* 2017). Lane *et al.* (2011) defines NFRM within the context of CBFM as a component of managing the sources and pathways of flooding by intercepting, slowing, storing and if possible, filtering flood water. This risk based approach is commonly applied using sustainable drainage schemes (SuDS), including Rural SuDS (Duffy *et al.* 2018) in order to manage flood flows across a management train approach (Lashford *et al.* 2014, CIRIA 2015). Both NFRM and Rural SuDS can be applied interchangeably, however, NFRM literature more commonly refers to Rural SuDS as a component of NFRM (Pearson 2016, Rose *et al.* 2015, Fraser 2015), applied in farms (either in fields or in farm yards) to treat effluent runoff before slowly discharging treated storm flow into the receiving watercourse. NFRM is used herein as the main term of reference.

Table 2.6 NFRM terms and definitions

Country	Term	Definition
England and Wales	Natural Flood Risk Management (NFRM)	"Taking action to manage flood and coastal erosion risk by protecting, restoring and emulating the natural regulating function of catchments, rivers, floodplains and coasts" (Ngai *et al.* 2018, Burgess-Gamble *et al.* 2018: 2).
England and Scotland	Natural Flood Management (NFM)	"A range of techniques that aim to reduce flooding by working with natural features and characteristics to store or slow down flood water, excluding traditional flood defence engineering" (Forbes *et al.* 2016: 6).
England and Wales	Rural Sustainable Drainage Systems (R SuDS)	"RSuDS comprise individual or multiple linked component structures replicating natural processes, designed to attenuate water flow by collecting, storing and improving the quality of run-off water within rural catchments" (Avery 2012: 4)
Scotland	Rural Sustainable Drainage Systems (Rural SuDS)	"Rural SuDS reduce agricultural diffuse pollution impacts as they are physical barriers that treat rainfall runoff. They are low cost, aboveground drainage structures that capture soil particles, organic matter, nutrients and pesticides before they enter the water environment" (Duffy *et al.* 2016: 1).
Europe-wide	Natural Water Retention Measures (NWRMs)	"Measures that aim to safeguard and enhance the water storage potential of the landscape, soil, and aquifers, by restoring ecosystems, natural features and characteristics of water courses and using natural processes" (EU 2014).
North America	Best Management Practices (BMPs): Cropland drainage	"Engineering with nature in order to achieve natural flood control. Drainage as part of an on-farm soil management system, and many complementary BMPs for erosion control, and healthy soils, cropland, and adjacent natural areas apply. Specific BMPs for surface drainage include inlets and erosion control structures" (OMAFRA 2016).

Slowing, storing, disconnecting and filtering flood flows are hydrological processes that can be enacted upon in singularity or collectively. Figure 2.14 provides schematics of these processes applied by example NFRM methods. These approaches will be discussed in greater depth in Section 2.5, within a meta-analysis of NFRM case-studies, including how the measures were identified and the flood risk performance of the schemes (modelled and/or observed). It must be recognised that each NFRM measure can also provide multiple hydrological functions, for example, a cross-slope woodland can slow (intercepting overland flows), store (intermittent retention, also known as attenuation), disconnect (intercepting flow that would otherwise converge, or relative peaks that would otherwise converge) and filter (infiltration losses through roots) (Nisbet *et al.* 2011, Wilkinson *et al.* 2013).

Figure 2.14 Hydrological functions of NFRM at the field-scale (adapted from FWAG South West 2017)

2.5 Natural Flood Risk Management Application: Systematic Review of Case-Studies

This section provides a comprehensive review of NFRM case-studies. Studies covered include those at the early stages of preliminary scoping, to implementation and evidence gathering. The aim of the systematic review of published literature and pooled reanalysis (e.g. McIntyre and Thorne 2013; Ngai *et al.* 2016) is to identify and assess specific elements of the case-studies, highlighted in Figure 2.15. The NFRM measures discussed are those applied in non-tidal NFRM schemes. Table 2.7 details all NFRM measures and associated types, based on common catchment application and functions. These are adapted from multiple guidance documents, principally the Environment Agency evidence directory (Burgess-Gamble *et al.* 2018) with the addition of hedgerows and wet woodlands, identified from the Dadson *et al.* (2017) NFM restatement and EU NWRM guidance (Strosser *et al.* 2015).

Table 2.7 NFRM interventions (adapted from Burgess-Gamble *et al.* 2018, Forbes *et al.* 2016, Dadson *et al.* 2017, Strosser *et al.* 2015)

Runoff Management	
Soil and land management	Conservation tillage, crop rotation, winter cover crops, reduced stocking density, vegetation cover and buffer strips
Headwater drainage	Track drainage and grip/gully blocking
Runoff pathway management	Bunds, ponds, swales and sediment traps
River and Floodplain Management	
River restoration	Re-meandering, deculvert and two-staged channels
Floodplain/wetland restoration	Embankment removal and restoring wetlands
Leaky barriers	Leaky debris dams, coarse woody debris and beaver dams
Offline/Online storage areas	Washlands, offline pond and online pond
Woodland Management	
Catchment woodland	Hill top woodland, large-scale woodland cover
Cross-slope woodland	Woodland belt and shelter belt
Hedgerows	Hedges and cross-slope interceptors
Wet woodland	Woodland water retention area and leaky deflectors
Floodplain woodland	Floodplain zone woodland and floodplain roughening
Riparian woodland	Riparian zone woodland and bank crest roughening

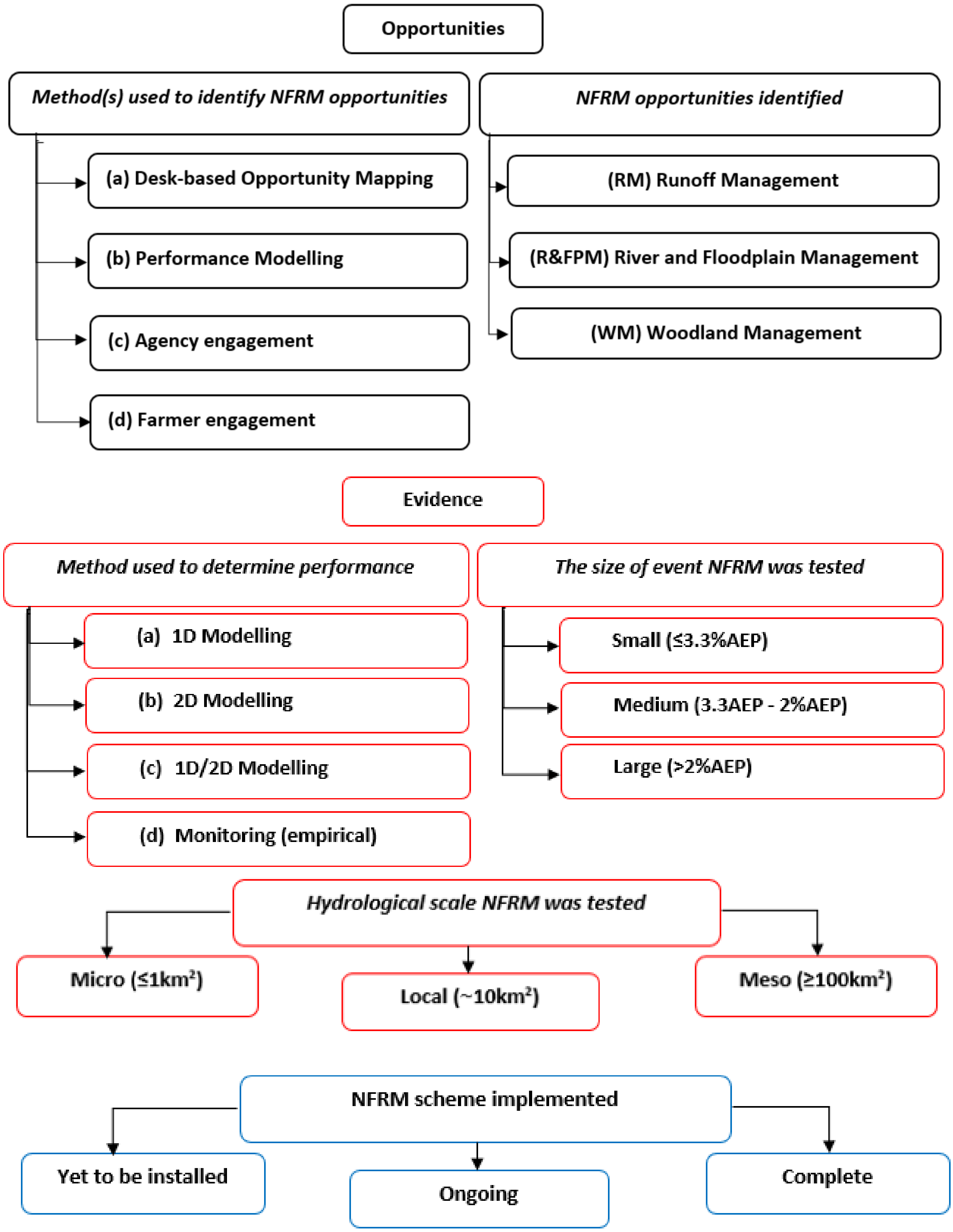


Figure 2.15 Elements assessed from NFRM case-studies. It must be noted the meta-analysis systematically reviewed those projects that are primarily aimed at reducing flood risk, of which some were also seeking multiple benefits.

The performance of NFRM approaches are considered site-specific and influenced by a myriad of local factors, including the area and hydrological-scale at which they are applied. Furthermore, it has been recognised it may not always be possible to guarantee a specified standard-of-protection (SoP) with NFRM. Consequently, FRM activities are normally assessed across the 'continuum of options' (Figure 2.16) ranging from traditional engineered defences to more NFRM approaches, with an extensive range of possibilities in between. The systematic review is concerned with NFRM interventions (outlined in Table 2.7, and discussed in Section 2.5.1).

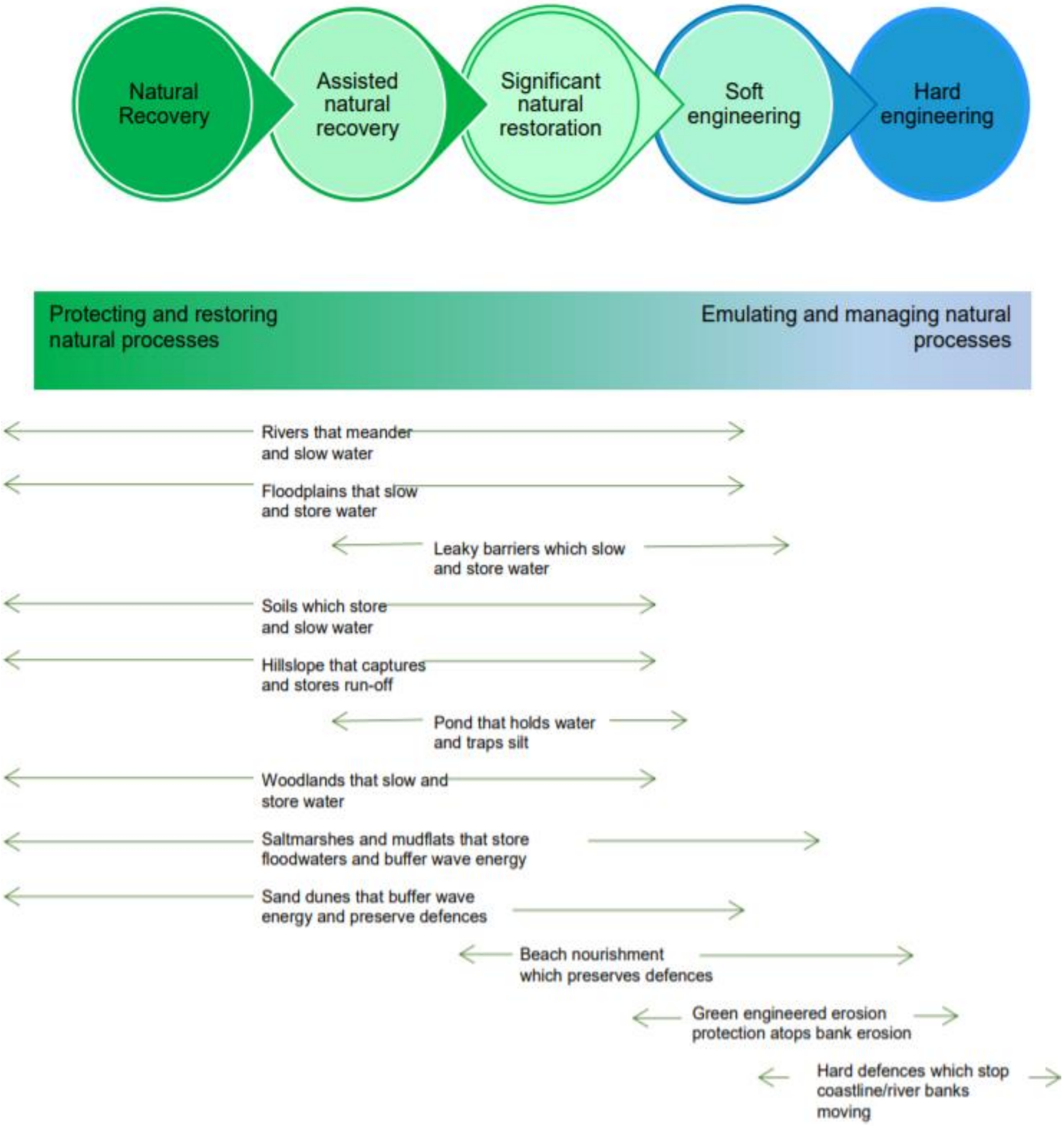


Figure 2.16 The FRM continuum (Environment Agency 2012a).

2.5.1 Natural Flood Risk Management Methods

Runoff Management

Runoff management techniques are those that intercept overland flow, improve soil structure to increase storage capacity, encourage infiltration and enhance the hydraulic roughness of flow routes (Quinn *et al.* 2007, Nicholson *et al.* 2012). These measures are often considered the most heavily engineered, utilising structures such as flow controls to become active and operational (Welton and Quinn 2011, Marshall *et al.* 2013). These methods are considered to manage flood risk by:

> i) Intercepting overland (surface water) flow routes and materially slowing the rate at which flood flows enter the receiving watercourse through increased hydraulic roughness (Letts 2012, Quinn *et al.* 2013);
>
> ii) Enhancing infiltration processes and increased soil storage by increasing porosity, enabling water greater soil water retention (MAFF 1970, Hudson 1995, Grable 1996, Greenwood *et al.* 1997, Hansen *et al.* 1999, Holman *et al.* 2003, Field and Auserwald 2006).

Soil and Land Management

Altering soil and land management in areas of high risk of hydrological connectivity can increase the number of storage features, infiltration losses and the overall capacity of soils store flood waters - ameliorating saturation excess overland flows in heavily saturated, poorly structured soils (Lane 2017). Table 2.8 outlines the different methods of soil and land management, including short descriptions.

Table 2.8 Soil and land management methods

Method	Description
Soil aeration	A method that improves soil structure by breaking compact topsoil and enables crop cultivation (Douglas *et al.* 1998), increasing the hydraulic conductivity of the soil column to increase infiltration and water storage capacity. Thus, reducing volumes and increasing travel times to the arterial drainage system.
Conservation tillage	Tillage (also known as soil cultivation), in the short term, has benefits for water storage in the soil by increasing porosity and reducing soil bulk density (BIO Intelligence Service and Hydrologic 2014). However, longer term, the permanency of healthy macro-pores are destroyed, disturbing soil structure and undoing the soils natural ability to store water (Strudley *et al*. 2008).
Winter crops	Winter vegetation protects the surface of the soil from 'capping' that commonly occurs from processes such as raindrop splash that seals the surface. Winter cover can increase organic matter of the soil, reduce erosion, enhance evapotranspiration losses and increasing the infiltration rate and ability for the soil to store water in roots and healthy soil columns (Environment Agency 2003).
Crop rotations	Defra (2017) recommended a 4-year crop cycle with one year in fallow (grass) to improve soil structure via reduced farming intensity and associated compaction.
Stocking density	In grassland systems, limiting grazing livestock commonly leads to a lessening in overland flows (Nguyen *et al.* 1998, Carroll *et al.* 2004). This is through the improved soil structure, enhancing infiltration and evapotranspiration losses.
Buffer strips	A buffer strip (or zone) can be situated anywhere in the catchment that conveys flow pathways to a receiving watercourse (Lane *et al.* 2007). This can be riparian areas of dense vegetation or regions in fields that can intercept overland flow routes, acting as a buffer (Gao *et al.* 2016).

Headwater Drainage Alteration

Headwater drainage alteration constitutes measures at the headwaters (also known as source) of typically small catchments (<10km^2) (Burgess-Gamble *et al.* 2017). In the highly diffuse networks of upland drainage patterns there are many opportunities to modify the flow regimes travel times and distributed storage by 'slowing the flow' before it reaches the larger receiving watercourse. Methods outlined in Table 2.9 covers both agricultural and peatland land management practices.

Table 2.9 Headwater drainage alteration methods

Method	Description
Track drainage alteration	The impermeable surface of farm tracks with smooth surfaces can concentrate flow (Zhao 2009). Cross-drains can laterally divert flows into adjacent ponds or fields, disconnecting flows (Evan 2006).
Gully blocking	Gullies can occur naturally, when blanket peat is spread on the head of valleys, or artificially when land drainage enhances erosional processes. Blocking gullies encourages vegetative cover, increases flood flows travel time, disrupting and spreading flow pathways. This method often creates attenuation pools behind the gully blocks, which provide additional storage features that can drain after the event in order to retain their capacity (Holden *et al.* 2011).
Grip blocking	Grip blocking (most commonly applied in peatland) restores natural drainage regimes, reducing the levels of erosion through revegetation in order to retain water upstream. Grip blocking dams generate pools of water in the peat, enabling the water table to recover from centuries of underdrainage and burning (Wilson *et al.* 2010).

Runoff Pathway Management

Runoff pathways enable hydrological connectivity between the landscape and receiving watercourse (Reaney *et al.* 2014). Management methods mimic natural hydrological regimes to ameliorate artificial drainage practices on overland discharge rates, reducing levels of pollution and flooding (Environment Agency 2012c). Methods outlined in Table 2.10 provide opportunities to regulate overland flows through floodwater attenuation, disconnecting flow routes, increasing travel times, and increasing hydraulic roughness during high flows (Nicholson *et al*. 2012).

Table 2.10 Runoff pathway management methods

Method	Description
Bunds	Commonly situated within overland flow routes, bunds (also known as beetle banks, earth bunds or clay bunds) are wide and shallow mounds of compacted subsoil that intercept concentrated runoff pathways (e.g. valleys, slope convergence or low field corner). See Figure 2.15 for example structure in Belford (Quinn *et al.* 2013, Avery 2012).
Ponds	Commonly situated in overland flow routes, ponds are depressions that provide water retention and flood storage capacity as either an attenuation features (temporary storage) or permanently wet pond with headroom capacity in a flood event (Forbes *et al.* 2016).
Swales	Linear, vegetated storage areas that slowly convey as well as attenuate storm flow, designed to intercept and move runoff (Duffy *et al.* 2016), also known as grassed waterways (Forbes *et al.* 2016).
Sediment traps	Similarly structured to ponds and designed in sequence, located in areas of surface flow accumulation (commonly in arable field corners) where sediment laden flows are intercepted, settled and then discharged (Avery 2012, Duffy *et al.* 2016).

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Figure 2.17 Runoff attenuation bund, Belford, Northumberland, England (Welton and Quinn 2011)

River and Floodplain Management

River and floodplain management techniques increase the morphological complexity and hydraulic roughness of the river networks and adjacent floodplains, in order to slow flood flows and reconnect (often disconnected) rivers from their floodplains for attenuation. Offline and online storage areas are considered the most heavily engineered, comprising of grey infrastructure such as flow controls in order to become active and operational (Burgess-Gamble *et al.* 2018). River and floodplain management methods are considered to reduce flood risk by:

i) Restoring in-channel features to slow river flows, increasing the reach length of the section of watercourse and intercepting high-flows through the introduction (or in some cases reintroduction) of woody material (Gurnell 1998, Wohl and Beckman 2011);

ii) Increasing connectivity between the river and floodplain laterally – attenuating storm flow within floodplains (Tweed Forum 2016, Gurnell *et al.* 2016) and;

iii) Vegetated floodplains and established wetlands, which encourage infiltration and enhanced soil water storage (Piegay *et al.* 2005, Addy *et al.* 2016).

Table 2.11 River and floodplain management methods

Method	**Description**
River restoration	Rivers have been materially straightened for land drainage, cultivation, navigation and development for centuries. Restoration is considered the reinstatement of natural processes (e.g. removing weirs) and features that are characteristic (re-meandering, adding woody materials) (Addy *et al.* 2016).
Floodplain/wetland restoration	Floodplain and wetland restoration restores the hydrological connection between floodplains and their rivers that have been historically drained, for settlement or cultivation. This can involve removing embankments and other man-made structures designed to keep floodplains dry, thus encouraging the formation of wetland areas, including fens, marshland and swamps, seasonally wet grassland and wet heathland (Winterbottom 2000).
Leaky barriers	Leaky barriers consist of lengths of wood (sometimes pleached and live), that would naturally accumulate in watercourses and floodplains. Whilst the term 'barrier' conjures views of hard engineering, leaky barriers are naturally occurring watercourse features with trailing and falling trees, snagging vegetation. In some studies these dams also form as a result of beaver re-introduction (Puttock *et al.* 2010). Beaver dams (also known as leaky barriers) can also be emulated by people to restore rivers and floodplains to slow and attenuate flooding (Nisbet *et al.* 2011a, Sear *et al.* 2010, Dixon 2013, Kitts 2010, Odoni and Lane 2010). Example image provided in Figure 2.5.4 (Uttley 2016).
Offline/online storage areas	Offline and online storage are mostly floodplain areas that have been altered to intercept and attenuate flood flows. Offline storage requires a containment bund which increases the volumes and levels of flood waters within an adjacent floodplain, infilled with a spillway and drained at an outlet. Online

	storage normally generates storage off both banks, restricting channel flows in flood events and encouraging backwater effects. These storage areas required more engineered outlets and headwalls due to hydraulic loads (Morris *et al.* 2004, Hardiman *et al.* 2009, Nicholson *et al.* 2012, Odoni *et al.* 2012)

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Figure 2.18 Leaky barrier, Stroud Frome, Gloucestershire. (a) low-flow conditions, and (b) the same structure during a flood event, notice additional storage in-channel and the floodplain (Uttley 2016)

Woodland Management

Woodlands are defined as land coverage with at least 20% canopy cover (Robinson *et al.* 1993). "Woodlands" and "forests" are used interchangeably in the literature, with reference to forests most commonly in North America (Hewlett and Helvey 1970). In terms of FRM, woodland management methods are considered to reduce flood risk by:

i) Intercepting flow routes, physically slowing the rate of flood flows to watercourses through greater hydraulic roughness; and

ii) Increasing infiltration and evapotranspiration losses by tree roots enabling infiltration to the soil and natural canopy interception and photosynthetic processes encouraging evapotranspiration losses (Robinson *et al.* 2003, EEA 2015). Table 2.12 provides different methods of woodland management.

Table 2.12 Woodland management methods

Method	**Description**
Catchment woodland	Refers to the total woodland area across a catchment, but most commonly applied at hill-tops. It combines the cover of woodland across all types and species (Best *et al.* 2003, Dixon *et al.* 2016).
Cross-slope woodland	The placement of woodland across hill slopes, typically in belts. The main purpose of cross-slope woodland is to intercept and reduce hydrological connectivity by increasing infiltration rates, soil water storage capacities and surface roughness (Marshall *et al.* 2014, Solloway 2012). An example of cross-slope woodland provided in Figure 2.5.5 (RSPB 2015).
Hedgerow	Hedges are small, linear reaches of tree planting, acting as cross-slope interceptors, increasing hydraulic roughness. This in turn slows down flood flows across the catchment, increasing the potential soil infiltration into the roots and evapotranspiration (Harris *et al.* 2004).
Wet woodland	Woodlands which are frequently (including seasonally) wet through flooding processes from streams or rivers, springs or overland flows (Brocklebank *et al.* 2005). These areas have declined due to urbanisation, land drainage and unsympathetic forestry practices (RSPB 2009). They generate backwater pools, increase hydraulic roughness with woodland undergrowth, and enhance evapotranspiration and infiltration losses (Sussex Wildlife Trust 2013).
Floodplain woodland	Defined as low lying woodlands within the floodplain, subject to various levels of inundation (intermittent, planned or natural). Species are typically broadleaved, with the aim of increasing hydraulic roughness of

	the fluvial floodplain to slow high-flows and encourage backwater effects (Puttock and Brazier 2014, Dixon *et al.* 2016).
Riparian woodland	Woodlands located along river banks (within a riparian zone) on land immediately adjoining a watercourse. This area is considered narrow stretches of afforestation, often extending <5m on either side of bank. For FRM purposes, this wooded area enables backwater effects and increases hydraulic roughness in-channel, especially at high flows. They also reduce erosion and channel incision processes, which can increase downstream conveyance (Dixon *et al.* 2016, Brown 2013, McIntyre and Thorne 2013, Odoni and Lane 2010)

Figure 2.19 Cross-slope woodland example, Clough woodlands, River Derwent, England (RSPB 2015).

2.5.2 Systematic Review of Case-Studies: UK and International

Figure 2.20 illustrates all UK NFRM case-studies assessed at part of the systematic review of non-tidal NFRM schemes with the primary aim of addressing flood risk. Figure 2.20 also outlines their current status, either ongoing (still undertaking scope, installing interventions) or complete (all interventions installed). The meta-analysis identified 82% of UK projects as ongoing, with only 8% classified as complete, in which all scoped interventions were installed with varying degrees of monitoring.

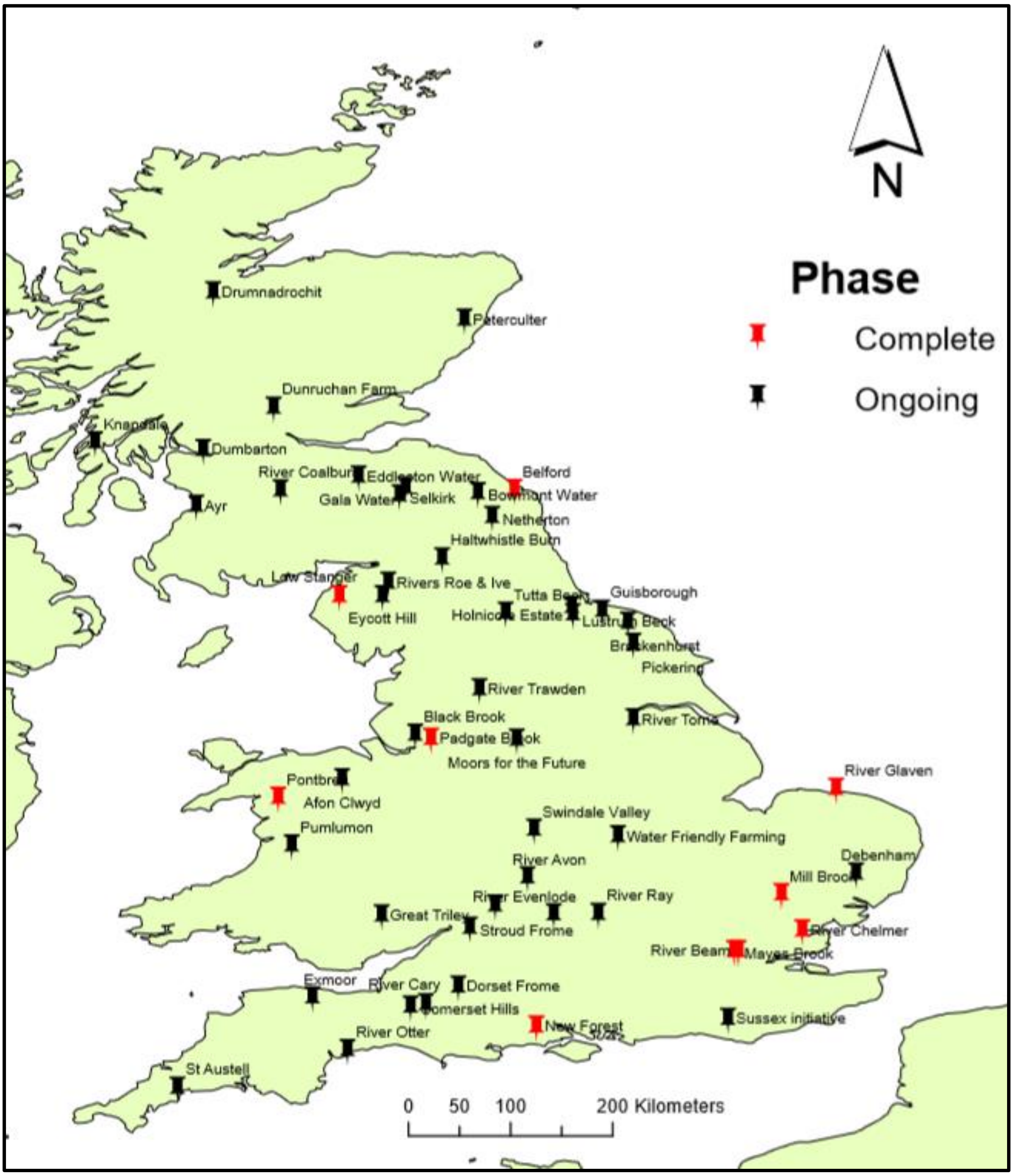


Figure 2.20 Overview of NFRM schemes across the UK (full systematic review provided in Appendix A).

Existing studies and schemes have been conducted at various scales. Figure 2.21 outlines the UK NFRM schemes and their catchment scales, with 54% applied at small catchment scales (≤10km^2) and only 14% applied to large catchments (≥100km^2). This pattern of NFRM application at smaller catchment scales is reflected in multiple evidence reviews that recognise a disproportionately few number of schemes at large hydrological scales (Dadson *et al.* 2016, Hankin *et al.* 2017, SEPA 2016).

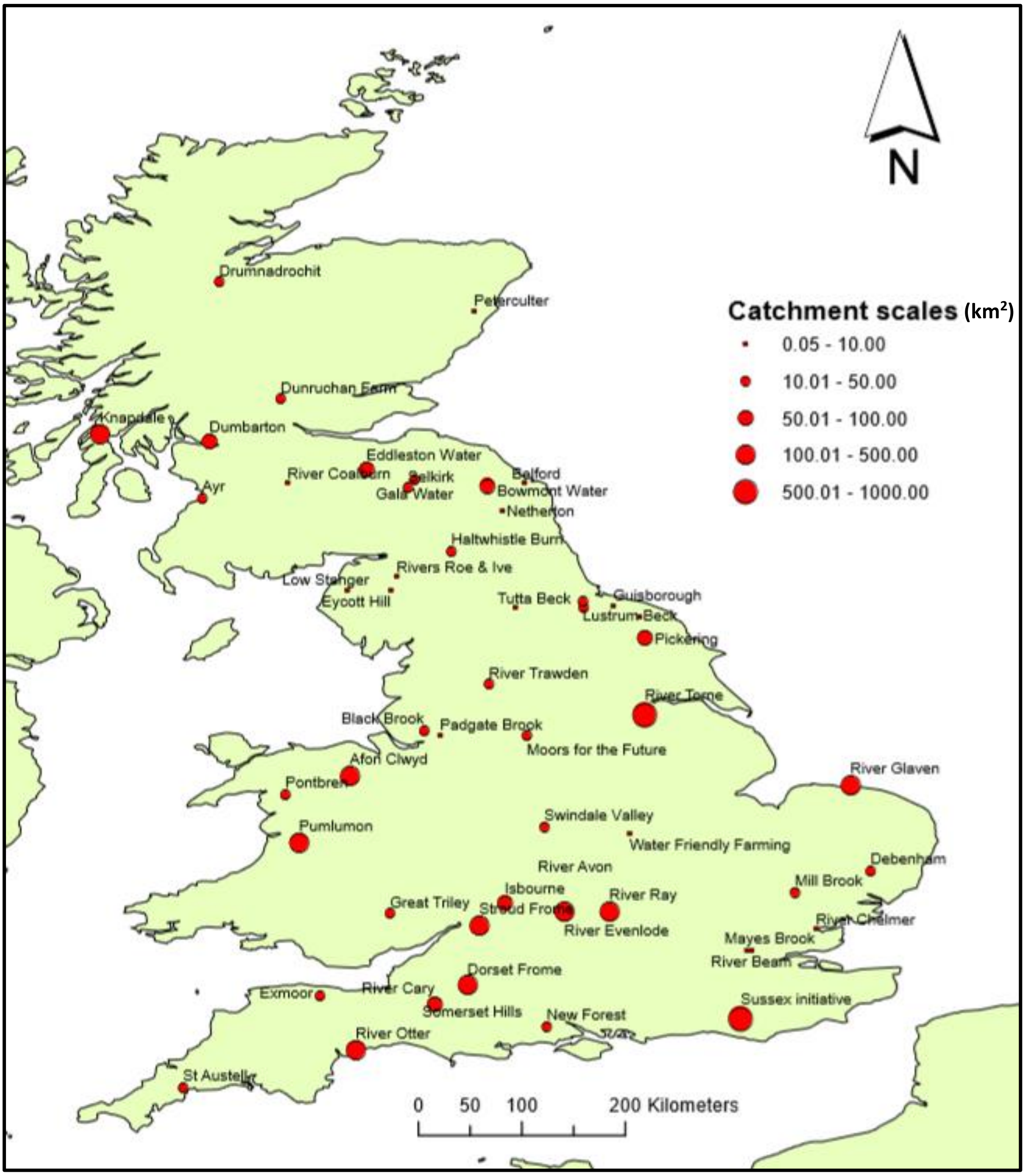


Figure 2.21 Overview of UK NFRM schemes and their hydrological scales (km^2).

Figure 2.22, outlines the different NFRM opportunities across the UK, classified based on types of interventions proposed and/or installed, including: River and Floodplain Management (R&FPM), Runoff Management (RM) and Woodland Management (WM). 62% of schemes, especially at larger catchment scales, include NFRM opportunities across the three distinct themes outlined in Table 2.7.

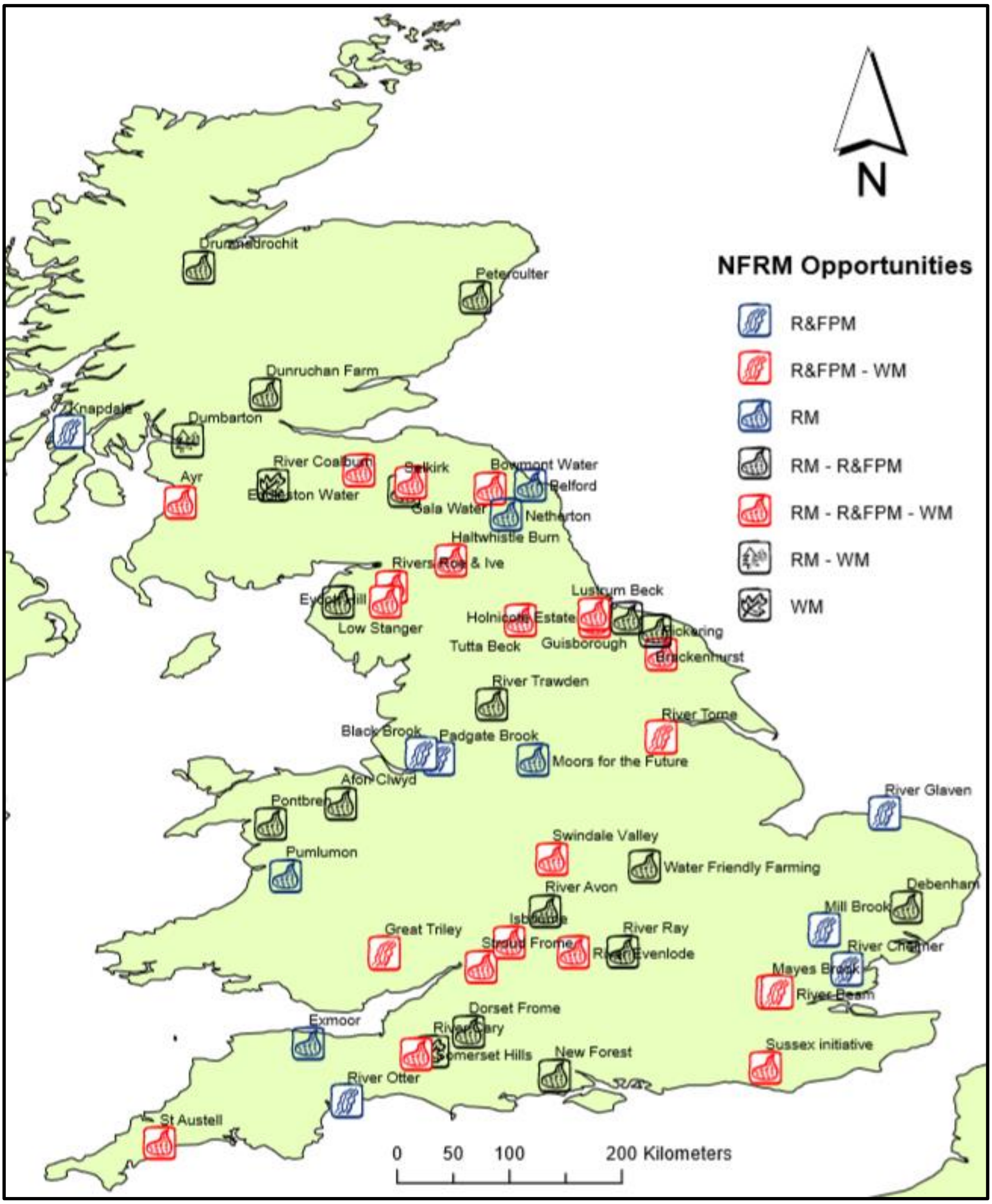


Figure 2.22 UK NFRM opportunities, classified based on types of interventions proposed and/or installed. Full information on types of measures applied in catchments provided in Appendix A.

In addition to the catchment scales and NFRM opportunities scoped, the methods to identify where to situate NFRM opportunities were also identified from the meta-analysis of literature. The frequency of each method is compared in Figure 2.23. The four dominant methods include:

i) **Desk-based opportunity mapping**: A remote study to identify possible locations for NFRM across a catchment, providing an indicative map of possible locations and in some cases types of NFRM. Examples include SEPA's national-scale opportunity maps in Scotland (SEPA 2013) and JBA's potential for WwNP national-scale maps (Hankin *et al.* 2017).

ii) **Prioritised modelling**: In some projects, a model scope was undertaken to inform where to prioritise NFRM across a catchment, such as a particular flashy tributary or converging at peaks. The whole catchment approach in the Eden undertook this method in order to prioritise efforts for future scoping (Metcalfe et al. 2018, Chappell *et al.* 2018).

iii) **Agency engagement**: In most projects, a relevant authority or professional partner was used to inform where NFRM could be situated. In a UK context, agency partners include the EA, SEPA, Local Authorities, Natural England, the NFU and Wildlife Trusts. These are non-academic partners that have used experience and expert knowledge to situate measures.

iv) **Farmer/landowner engagement**: The systematic review of literature found this to be the least commonly applied method to situate NFRM, where farmer/landowner engagement approach was used to inform what and where interventions could be undertaken to varying levels of involvement. For example, in the Stroud Frome, the project partners with farmers at the onset before any prior site analysis has been undertaken to encourage endorsement and early involvement (Short *et al.* 2017). However, the systematic review identified most projects engage after opportunities have been identified as a form of consultation through focus groups, not individual farmers and landowners, in order to obtain permission for the proposals.

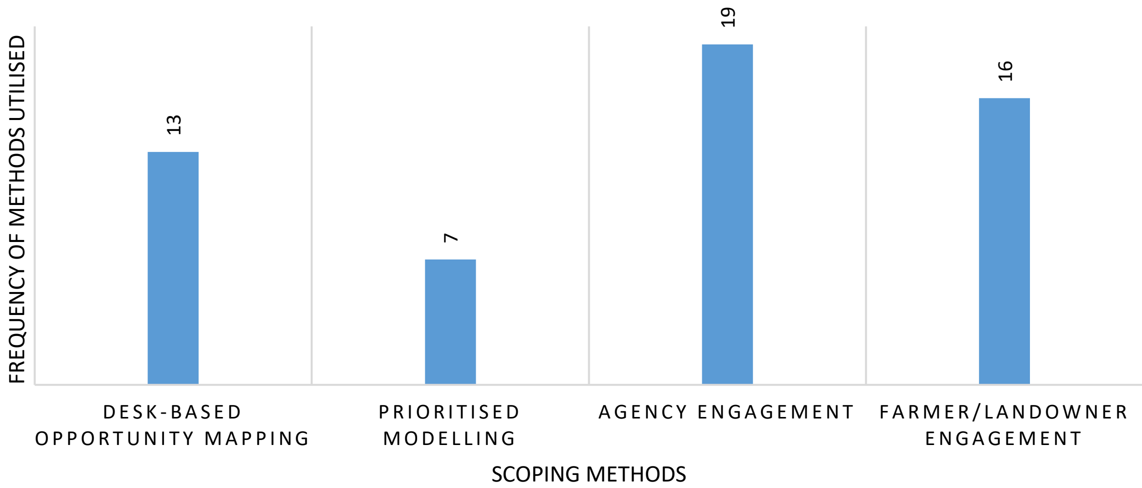


Figure 2.23 Frequency of methods utilised identifying NFRM opportunities

Published NFRM case-studies have been identified in continental Europe, North America and New Zealand. Figure 2.24 identifies NFRM schemes across continental Europe that have the aim of reducing flood risk. These schemes are displayed in terms of phase, catchment scale, and methods utilised to identify potential opportunities.

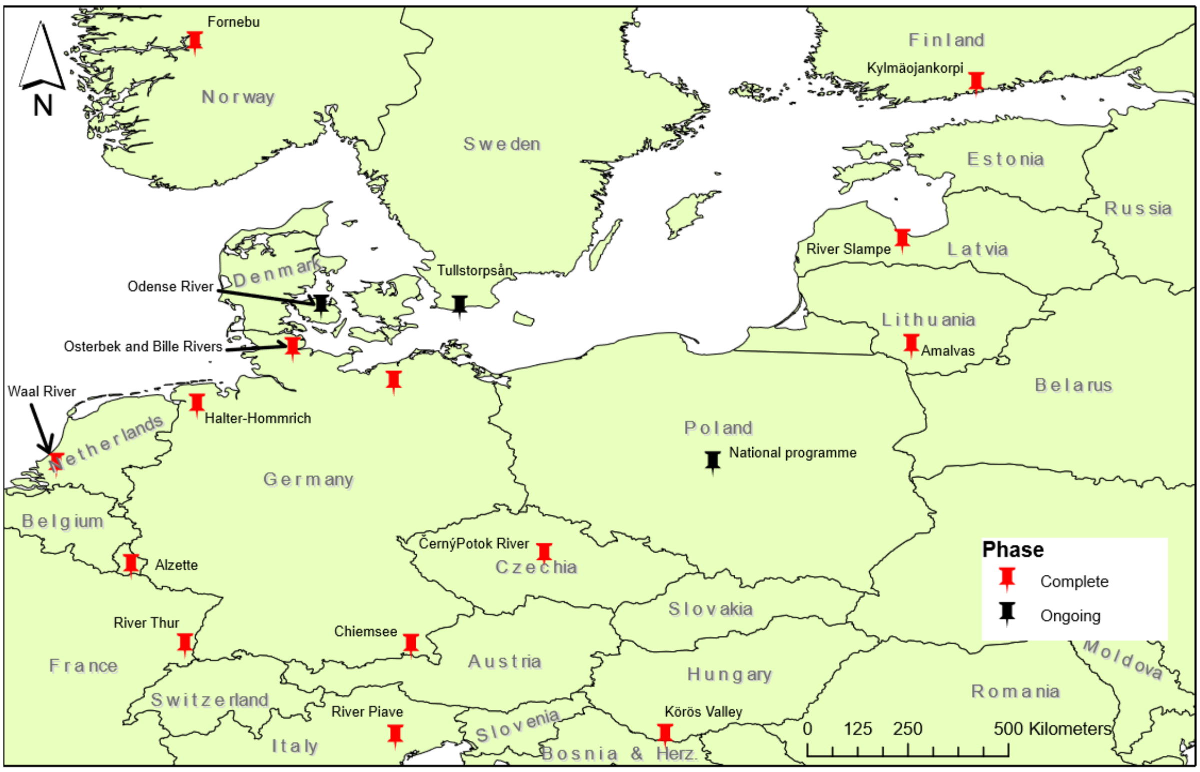


Figure 2.24 Overview of NFRM schemes across continental Europe

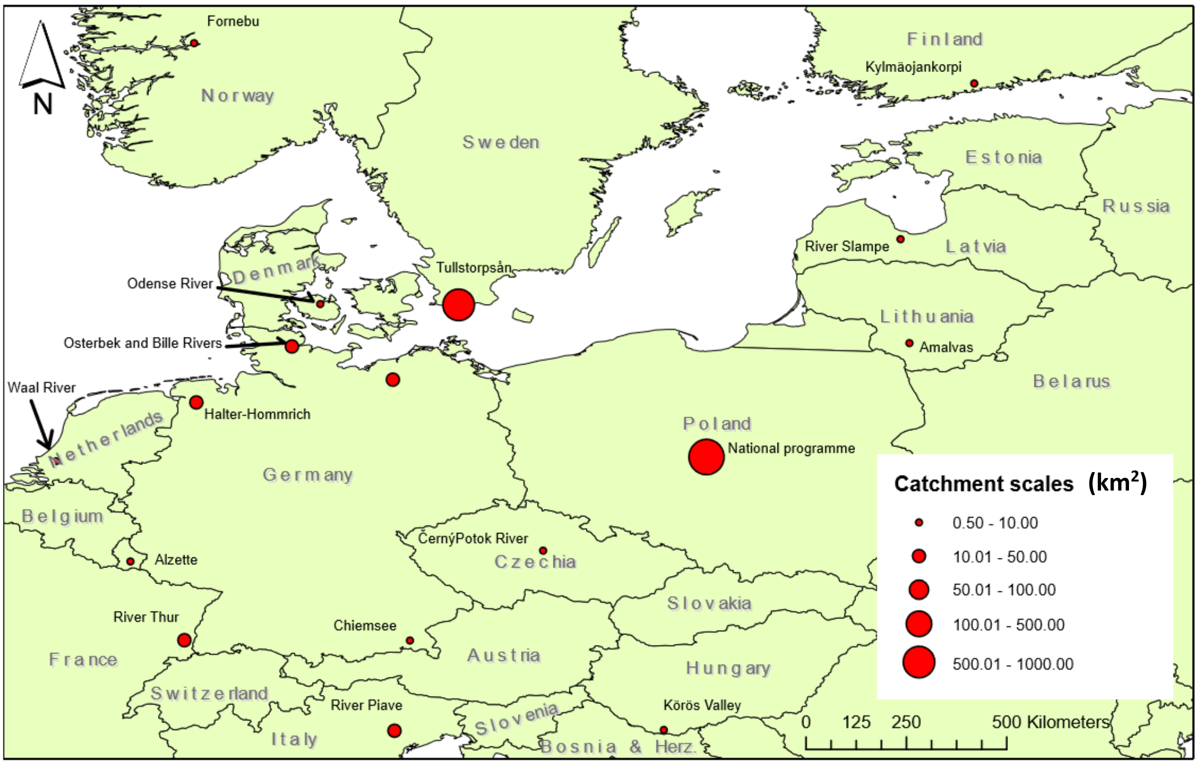


Figure 2.25 Overview of NFRM schemes catchment scales across continental Europe

Figure 2.25 provides an overview of the different NFRM interventions applied across each case-study in continental Europe. Unlike the UK, the majority of schemes involve methods of River and Floodplain Management (R&FPM), predominantly larger scale river and floodplain restoration schemes. Many of these schemes involve estuarine rivers that drain into the North Sea, with fluvial and tidal components within their management. For example, the Wall River scheme, Netherlands, restored a 1.8km reach as part of the 'room for the river' programme. The dike installed in the 1920s to protect farmland was moved back by 350m providing 16,000 m^3/s additional storage. Flood risk benefits were modelled, however there was a reluctance to participate by landowners. A lengthy period of negotiation and land purchase orders enabled the scheme installation (Williams and Jansen 2015, Rijke *et al.* 2012). In some instances, river restoration has also been delivered with floodplain restoration, changing not only the channel profile to encourage out-of-bank flows, but also increase hydraulic roughness reverting intensively farmed floodplains back to woodlands. The Lenzen River scheme, Germany, employed such a technique by reconnecting 420ha of floodplain with dike relocation, providing 16 million m^3 of additional storage, with the potential of attenuating flood peaks by up to 40cm (Damm *et al*. 2011). The interventions outlined in Figure 2.26 were identified by multiple methods. Unlike UK case-studies, landowner and farmer engagement was more comprehensively conducted in the identification of opportunities, and undertaken in earlier stages of the scope in order to obtain input.

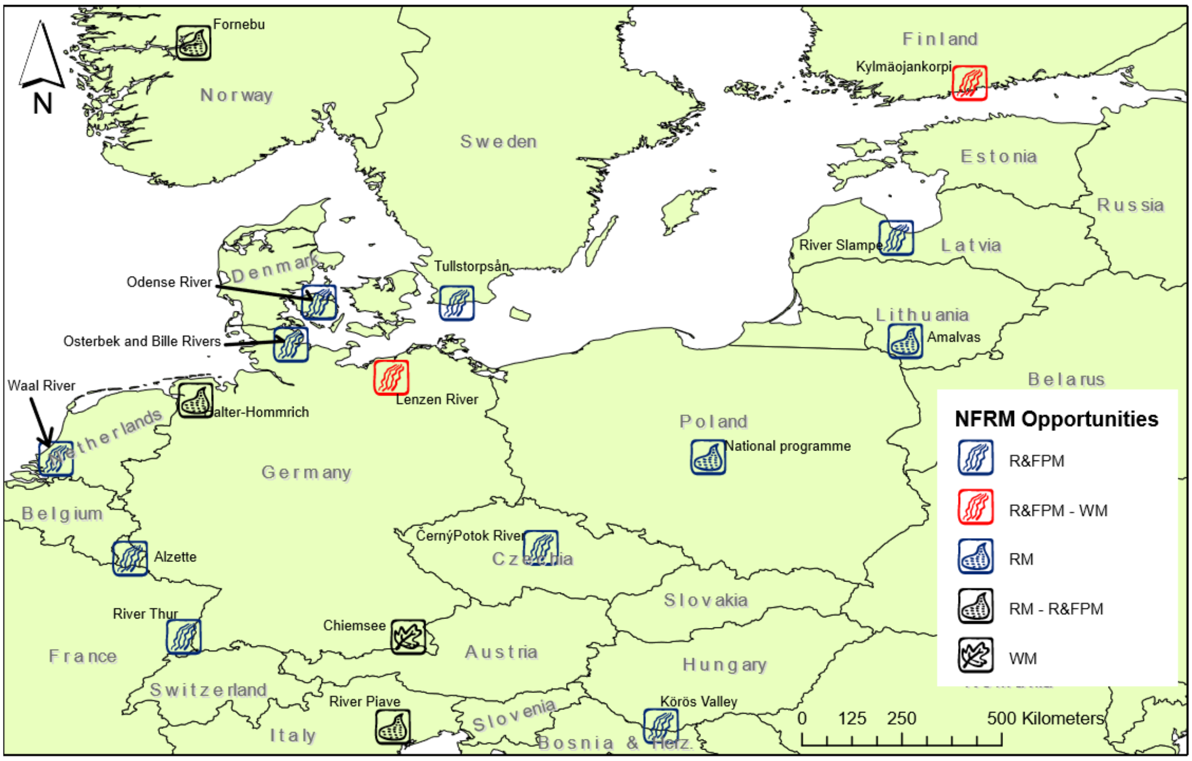


Figure 2.26 Overview of NFRM schemes and types of interventions applied across Europe

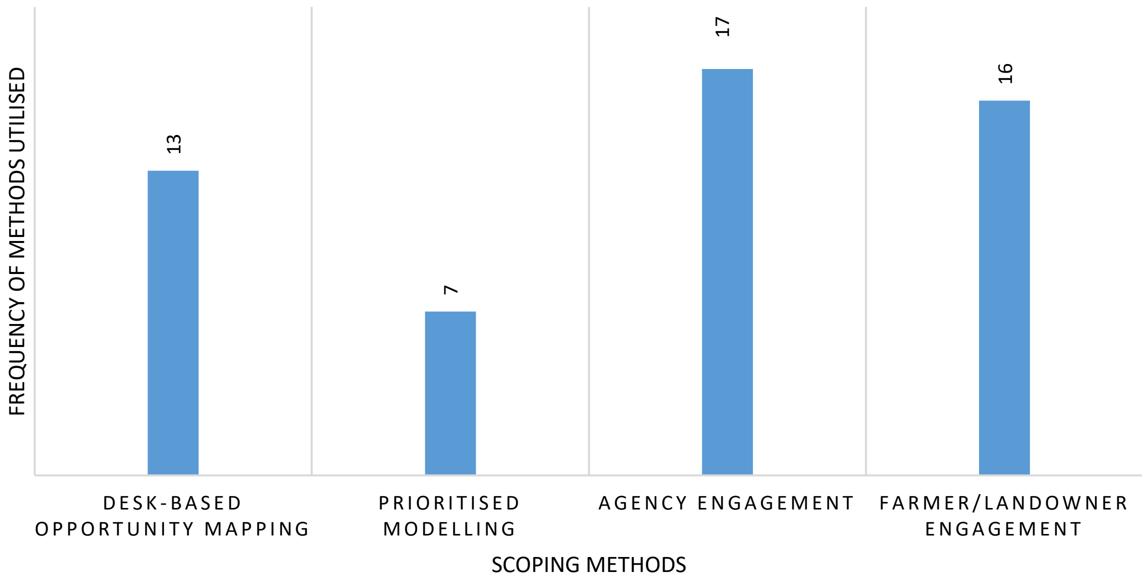


Figure 2.27 Frequency of methods utilised identifying NFRM opportunities across Europe

In relation to the flood risk performance of the NFRM schemes, 63% of case-studies obtained data on the effects of the schemes to varying degrees and hydrological scales. The performance of NFRM was significantly mixed based on the method of analysis, scale applied and interventions tested. Schemes were commonly tested on their ability to provide peak attenuation by increasing the lag-time (also known as time-to-peak), provide additional upstream storage and provide a standard a protection (SoP) to a certain sized flood event. Figure 2.24, outlines the performance of the schemes based on modelled and/or observed data to the above criteria. In the case of most implemented and monitored schemes, they have yet to be tested to large events (≥1%AEP), however, those that have been modelled (but often not installed) have been modelled to large events and their potential performance analysed.

Synthesising performance findings from the systematic review identified that small floods (≤20%AEP) in small catchments (≤10km^2) may be significantly mitigated by NFRM, yet there is no evidence NFRM will have a significant effect at considerably reducing risk (exposure) on the most extreme events. Heavy and intense precipitation on saturated (or impermeable) ground is considered the primary cause the large fluvial flood events. Furthermore, this chapter has also reflected that a high magnitude flood event could be so large that it will overwhelm any FRM measures, natural or otherwise. Mitigative measures that provide localised flood risk gains have not been shown to upscale to the large catchment-scales (≥100km^2). Whilst extrapolating these local benefits of many small measures theoretically could culminate to ascertain flood risk reductions at meso-scales, it cannot always be the case due to: (i) local peak attenuation are attributed to the network of rivers, and (ii) interactions between localised rainfall events across a network of tributaries can converge (also known as synchronise) peaks, exacerbating the problems downstream. However, this phenomena has only been modelled and not observed in any projects. The complexity of such catchment dynamics relies on a wide variety of parameters to occur as simulated, including rainfall amount, duration, location and antecedent conditions (Chappell *et al.* 2017).

Where multiple interventions are being tested it has been challenging to extricate the performance of an individual NFRM techniques, the role of which is highly dependent upon the tested catchments characteristics (in particular scale, basin shape, land use, land cover, infiltration patterns and hydrological connectivity), rainfall scenario and the number and locations of the NFRM measures within the catchment. With current scientific understanding, it cannot be stated unequivocally that NFRM provides significant flood risk benefits across large hydrological. However, this maybe because a sufficiently intense and diffuse set of NFRM measures have not been installed and tested.

However, across the projects that have quantified NFRM's flood risk performance, it seems there is a directly inverse association between (i) the size catchment and size of event and, (ii) the scope for managing catchment flood risk with NFRM. The large the size of the catchment and the greater the event, the lesser the scope for NFRM. Outlined in Figure 2.28, the Belford scheme, Northumberland, modelled a 30% peak reduction to a 1%AEP scenario across the 5.7km^2 catchment (Halcrow 2006, Quinn *et al.* 2015, Nicholson *et al.* 2018). However, Lustrum Beck, Stockton on Tees only modelled an 11.5% peak reduction to the same sized event over the 50km^2 catchment (Reed and Thomas 2018). Whilst the 18.5% difference is indicative of NFRM performance across different catchment sizes, there are a myriad of parameters that influence the performance of NFRM.

The main conclusions from the literature regarding performance: (i) NFRM that increases the soils ability of store water (via changes to land management and cover) have the greatest effect in smaller events at smaller hydrological scales. Once soils are heavily-saturated, effect are considered negligible and saturation-excess overland flows occur. (ii) storage features (e.g. ponds, bunds natural and attenuation basins) can effectively reduce downstream flood risk, depending on the volumes, numbers and locations of storage features, and when and how they are used; and (iii) enlarging the cross-sectional area of fluvial floodplains by removing (or setting back) infringements such as embankments that have disconnected rivers and their floodplains can reduce downstream flood peaks considerably.

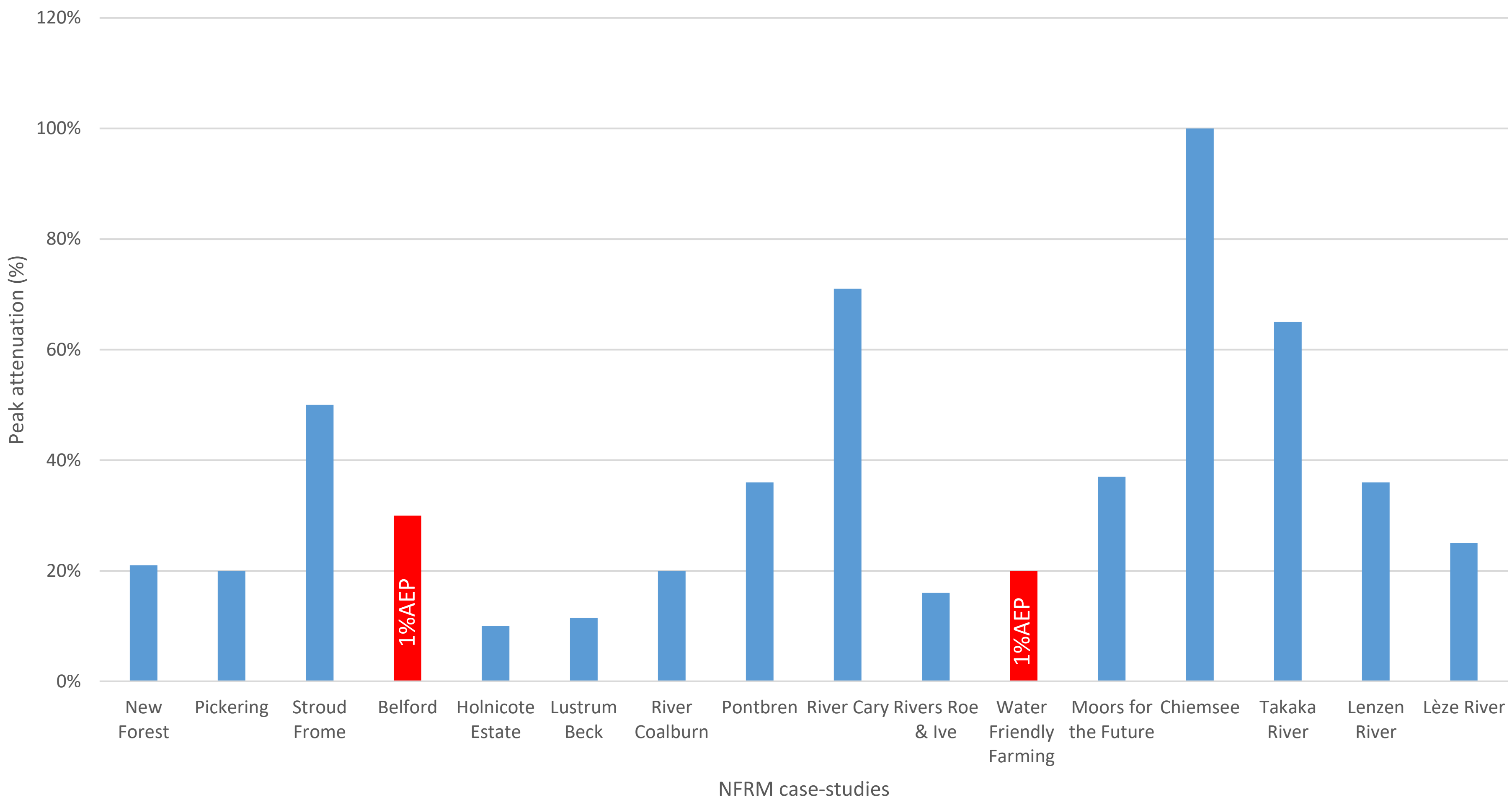


Figure 2.28 Downstream peak attenuation (%) identified across case-studies that undertook quantifiable assessment (modelled and/or observed) of peak reduction. Two were based upon large events (1%AEP), the majority of schemes peak reductions are based upon smaller events (≥2%AEP).

The systematic review of 75 UK and international case-studies indicates most projects (74%) are still ongoing, collecting more evidence through modelling and/or monitoring to determine the performance of NFRM schemes. Of the studies still ongoing, only 29% have installed any NFRM interventions, with many still awaiting funding after the 'scoping phase' (having undertaken opportunity mapping and high-level modelling). As part of the systematic review, the scoping methodology, hydrological scale of application, and performance of NFRM will be discussed.

2.5.2.1 Identifying NFRM Opportunities

In order to identify NFRM opportunities, 65% of the projects employed desk-based opportunity mapping, analysing a wide range of catchment characteristics, flow pathways and flood extents to indicate the locations and types of possible interventions. 51% also used models (mostly 2D) to clarify these NFRM opportunities by determining how they perform to modelled rainfall scenarios. Most projects (74%) sought to engage local agency partners (typically RMAs) to obtain partner knowledge of the catchment and farms, this included 12% that also involved local residents and organised community groups (e.g. flood action groups). 37% of studies engaged (or are planning to engage) farmers, but many studies referred to the engagement processes as a form of obtaining 'permission' (30% of the farmer engagement approaches). Very few approaches (7%) engaged landowners and farmers to obtain local knowledge to incorporate into the NFRM scoping. The projects that used local farmers' input in early stages (e.g. Stroud Frome, Somerset Hills to Levels and River Ray) did not provide the methodology for how they co-designed NFRM opportunities across the catchment areas. These projects refer to the need for a 'bespoke' approach per farm and farmer in order to identify opportunities, as each farm will have complex characteristics involving drainage and land management practices that need careful consideration (Short *et al.* 2018), and each farmer will have different motives for being involved in an NFRM scheme (e.g. stewardship funding, community empathy, amenity etc.) (NFU 2015, Waylean *et al.* 2016, Holstead *et al.* 2015). However, Environment Agency (2015), Burgess-Gamble *et al.* (2017) and Johnson (2017) recognise the research and application needed to devise a consistent framework to engage farmers in situating NFRM.

2.5.2.2 *Hydrological scale of application and NFRM performance to multiple flood risk events*

Hydrological scale and types of interventions are closely related to catchment-based NFRM performance. In small catchments (<10km^2) there is strong evidence for the reduction of flood risk by NFRM methods to small flood events demonstrated in Figure 2.28. However, whilst many projects have not been able to determine the NFRM performance at large hydrological scales to sizeable rainfall events, a simple extrapolation of the evidence provided in Figure 2.28 could infer the potential for an aggregation of marginal gains in more features were applied at larger catchment scales. However, it cannot necessarily always be attributed to this because either: i) local flood risk reductions are diminished downstream by the river network, thus hydrological dilution can negate any cumulative gains in the river network, and; ii) sub-catchment interactions between spasmodically variable storms mean that the separated peaks in one tributary can lead to the convergence of multiple sub-catchments. Therefore, evidence suggests the greater the catchment-scale and the larger the size of the flood event, the less opportunity there is for a CaBA to ameliorate flooding through a highly distributed NFRM scheme.

In terms of types of interventions, soil and land management that seeks to encourage soil infiltration and retention (including woodland planting, reduced grazing, soil aeration, sub-soiling and conservation tillage in arable systems), modelling and some limited monitoring studies suggest they are most effective for smaller flood events at small hydrological scales (Acreman *et al.* 2003, 2011, Marshall *et al.* 2014, Smith 2012, O'Connell *et al.* 2007, FWAG South West 2016). Runoff attenuation and floodplain storage measures, including ponds, bunds, swales and large offline and online storage areas, can effectively reduce downstream flooding, dependant on the volume of additional storage, location of structures and how and when the measure becomes active. The most confidence in NFRM performance is associated with river restoration methods, such as removing embankments and re-meandering, which increases lateral connectivity to the floodplain. These are commonly applied at the further downstream extents of catchments where determining hydrological processes is better understood (McIntyre and Thorne 2015, Ngai *et al.* 2018).

2.6 Chapter summary

From this literature review and systematic review of NFRM case-studies, it is clear O'Connell *et al.*'s (2004) review is still applicable, confirming there is limited empirical evidence that links rural land-use and catchment-scale fluvial flooding. Since war-time intensification of agricultural land (McIntyre *et al.* 2010), rapid urbanisation including floodplain encroachment (Fielding *et al.* 2010) and climate change impacts on hydrological systems (Cabinet Office 2008), policy and practice have begun to favour a CaBA that manages these complex and changeable systems more holistically (Section 2.3.1), encouraging NFRM activities that incorporate a host of local stakeholders (Section 2.3.2). The current status of NFRM evidence outlined in the systematic review, developed from various reviews by the Environment Agency (2017b), SEPA (2015), CREW (2017), NWRM (2017) and Macintyre and Thorne (2015) recommends the need for further quantification of performance. Therefore, published research has largely focused on modelling and monitoring (the latter to a lesser degree) to understand the effectiveness of NFRM (Dixon *et al.* 2016 and Hankin *et al.* 2017). This has limited the published research into engagement and communication methods (especially with farmers and landowners), with the exception of 'grey' literature studies, and studies into farmer and landowner attitudes (Posthumus *et al.* 2008, Holstead *et al.* 2017, Waylean *et al.* 2017).

Whilst NFRM has been advocated, literature and case-study analysis suggests that local engagement, particularly of farmers and landowners, has not been employed in many LFRM and NFRM schemes. This has the following negative effects: i) prohibiting uptake of WwNP schemes, and, ii) failure to source valuable 'place-based' local knowledge that can identify problems and local solutions. Therefore, due to a systematic review of UK and international NFRM case-studies (section 2.3.3) this chapter has raised four critical research questions regarding the engagement of farmers and landowners, which includes those completed NFRM schemes (see Figures 2.20 and 2.24). It is assumed that they have engaged with the farmers and landowners in order to install NFRM, but no detail was given on how this was achieved, including the data, methods and tools needed to identify opportunities. The four critical research questions raised from this review are:

- How can farmers and landowners be engaged to co-design NFRM schemes?
- How able and receptive are farmers and landowners to identifying sources and pathways of flooding?
- How receptive are farmers and landowners to incorporating NFRM schemes as part of their land use?
- If receptive, what sort of NFRM methods are farmers and landowners inclined to adopt?

These research gaps principally enquire “what can we do?” and “where can we do it?” through a participatory, transparent and replicable framework to co-design NFRM. Existing farmer engagement tools have been reviewed, including high-level opportunity mapping tools (e.g. JBAs WwNP Tool and SEPAs NFRM Opportunity Maps) Table 2.5, Section 2.5.1. The review of these methods and tools will be applied in the methodology to *co-design* NFRM through a Participatory GIS approach, as opposed to seeking *permission* or *approval* (further discussed in Chapter 3).

3 Methodology

3.1 Overall outline

This chapter explains the methodology adopted for the research, addressing the aims and objectives outlined in Chapter 1. Table 3.1 identifies sections within this chapter which explain the methods associated with each objective and the relevant results sections. The methods applied enabled the co-design of NFRM opportunities, and assessed the suggested scenario's performance across hydrological scales to multiple flood risk events. Sections 3.2 and 3.3 details the remote data sources used to characterise the catchment area. Section 3.4 introduces the novel Participatory GIS (PGIS) framework employed to co-design NFRM opportunities across the Stour valley, Warwickshire-Avon study site. Section 3.5 details the distributed hydrodynamic model used to calculate PGIS-NFRM performance to different flood events and the method use to quantify the role of NFRM.

An overview of the research framework is provide in Figure 3.1.

Table 3.1. Summary of methods and results sections for each aim and objective

Aims and Objectives	Methodology section	Results/ Appendix section
Aim 1: Undertake a desk-based characterisation of the catchment area		
1.1 Undertake a data mining exercise, collating and reviewing remote data to inform hydrological, geological, pedological land cover and land-use characteristics of catchment area.	3.3	4.3, 5.3
1.2 Physically, hydrologically and socially characterise the catchment in ArcMap.	3.4	4.2
1.3 Generate clipped base maps to each farm and estate from catchment characterisation to include in Farm Information Packs (FIPs) for Participatory GIS (PGIS)	3.4	4.2, 4.5 and 5.2. FIP in Appendix D

Aim 2: Identify NFRM opportunities across the catchment area		
2.1 Actively engage with all landowners/farmers [participants] across the catchment to arrange PGIS exercises	3.5	4.3, 5.2
2.2 Identify sources and pathways of flooding on each participants farm and estate	3.5	4.2, 4.3, 4.4, 5.3
2.3 Identify and co-design NFRM opportunities to address the sources and pathways of flood flows on each participants farm and estate	3.5	4.2, 4.3, 4.4, 5.3
2.4 Digitise NFRM opportunities in GIS as shape and point file layers, and confirm with participants	3.5	4.2, 5.3 Appendix E
Aim 3: Model the performance of the PGIS-NFRM scenario to multiple storm events		
3.1 Build a large, delineated 1D/2D hydrodynamic based model of the whole catchment area	3.6.2	6.3.
3.2 Generate FEH design storm input hydrographs (QMED, 3.3%AEP, 1%AEP and 1%AEP + 35%)	3.6.3	6.2, 6.3
3.3 Calibrate model and FEH storms to observed flow data, including sensitivity analysis to identify and reduce uncertainty (where possible).	3.6.4, 3.6.6	6.3
3.4 Simulate the baseline 'do nothing' scenarios, across multiple hydrological scales and flood risk events	3.6.2, 3.6.5	6.3
3.5 Simulate the PGIS-NFRM scenarios, then identify and assess any benefits and/or disadvantages of NFRM across multiple hydrological scales and flood risk events.	3.6.2, 3.6.5	6.3, 6.3.5

3.1.1 Research approach

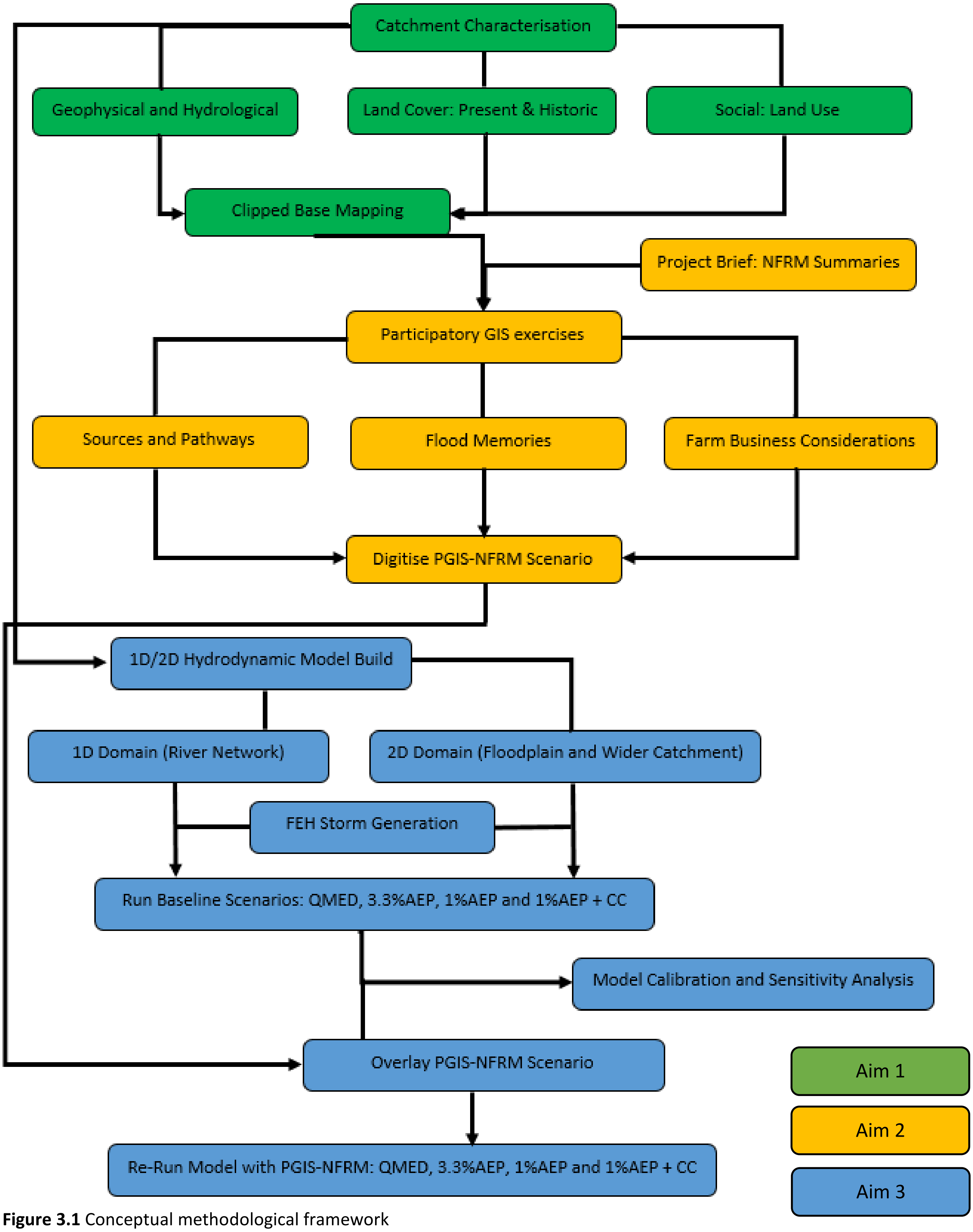


Figure 3.1 Conceptual methodological framework

3.2 Ethical Approval

Ethical approval was acquired and adhered to for this project according to Coventry University's research procedures. The purpose of the research was clearly outlined to all anonymised farmers and landowners involved in the PGIS framework. The relevant forms, including participant inform sheet, informed consent form and risk assessment are provided in Appendix B. The latter was required due to the lone working, participatory nature of the research, in which the participants conducted the mapping exercises with the researcher on their own farms and estates across the catchment area. It was also important as part of the informed consent to acknowledge the research was not accusing farmers and landowners of 'poor farming practice', but working with participants to co-design NFRM.

3.3 Catchment data sources and application

This section outlines the GIS desk-based steps used in meeting aim 1, involving data sourcing and processing to generate farm information packs (FIPs), in order to inform the PGIS co-design framework of NFRM opportunities, and subsequently assess their performance across multiple flood risk scenarios and scales. Table 3.1 identifies the data requirements for the PGIS framework (aim 2). This includes a detailed risk-based understanding of the flooding mechanisms, including the sources, pathways and receptors of flooding across the catchment scale, conceptually outlined in Figure 3.2.

Sources: fluvial, pluvial and groundwater. **Pathways**: flow pathways overland, sub-surface and in-channel, breaches and areas of inundation. **Receptors**: areas affected by flooding, mainly property, people and infrastructure. **Frequency**: how often the flooding has occurred and how long it lasts. **Extent of hazard**: depth of water, discharge and speed of onset. **Consequence of flooding**: property, business and infrastructure at risk

Figure 3.2 Conceptual source pathway receptor relationship across the catchment scale, how local scale runoff generation (potential source), propagates through the river channel network (pathways) to affect flooding downstream (the receptor).

To undertake this assessment, existing evidence and data found from open-access sources and in-house bespoke data held by Lead Local Flood Authorities (LLFAs), the Environment Agency (EA), Natural England (NE) and the Centre for Ecology and Hydrology (CEH), were used under license agreements. The data supports PGIS-NFRM Opportunity Mapping and the development of 'constraints and sensitivities' layers, in which each type of intervention has a specific constraint and sensitivity; for example existing woodland cover could be a constraint to further afforestation. Table 3.1 outlines the nationally consistent data sources, owners, licenses and purposes, with the majority of the data sources being used under an open source or open government licence (OGL).

Similar to experiences of previous NFRM scoping studies (e.g. SEPA 2013, Broadmeadow *et al.* 2016, Hankin *et al.* 2018) not all available GIS data was in a appropriate form and level of detail, necessitating alternate approaches in the form of local engagement with farmers and landowners to co-design adoptable NFRM opportunities. Farm surveys as part of the PGIS process were considered necessary to provide land management details, as well as details of localised drainage practices and historic flood events obtained by digitising flood memories (McEwen *et al.* 2012), further discussed in section 3.5.

The data sources, presentation and analyses techniques are presented in the pilot farm assessment to critique the NFRM co-design method at the farm-scale, with the purpose of reflecting on the method before upscaling to the whole catchment extent. Details of the pilot farm study, and its assessment of NFRM opportunities, are included in section 4. The data used in the modelling aspect of the methodology meeting the third aim is provided in Table 3.1 and discussed in section 3.6.

Table 3.1 Desk based data shortlist, in regards to catchment characterisation (first aim) NFRM-PGIS opportunity mapping (second aim) and performance modelling (third aim).

Title	Owner/Source	License	Purpose
National Receptor Dataset (NRD 2016)	Environment Agency	Conditional – not published	Background derivation data to inform current exposure to properties and businesses.
OS Open Local (Vector)	OS	Open data	Background mapping
OS 1:1000 (Raster)	OS	Open data	Background mapping
OS 1:2500 (Raster)	OS	Open data	Background mapping
OS 1:250000 (Raster)	OS	Open data	Background mapping
Aerial Imagery	Google Earth	Open data	Background mapping
Cadastral land boundaries	RPA	Conditional – not publish	Land boundaries, including ownership details, across catchment area
Detailed River Network (DRN)	Environment Agency	Conditional – not published	Background derivation data to display watercourse network, including high order stream networks
River Basin Districts (Cycle 2) – WFD	Environment Agency	OGL	Background derivation data to display basin boundaries, as defined under the Water Framework Directive
Water Body Catchments (Cycle 2) – WFD	Environment Agency	OGL	Background derivation data to display catchment boundaries, as defined under the Water Framework Directive
LiDAR 2016	Environment Agency	OGL	Digital Terrain Model (DTM) generation, to display slope, channel profile and hydrological connectivity. Areas of steep profile valleys (>45°) directly feeding receiving watercourses indicate high hydrological conductivity.
Hydrology of Soil Type (HOST)	CEH	Conditional – not published	Pedology of catchment, to display infiltration patterns and influences of standard percentage runoff. This also informs suitable areas for schemes that encourage enhanced infiltration losses (e.g. HOST class 2) and address areas with greater runoff problems (e.g. HOST class 20).
BGS Bedrock and Superficial Geology 625,000	BGS	OGL	Geology of catchment, to display infiltration patterns and wider catchment characteristics. This also informs suitable areas for schemes that encourage enhanced infiltration losses (e.g. free draining limestone).
SPRHOST	CEH/Cranfield	Conditional - not published	Standard percentage runoff (%) associated with each soil class to derive SPRHOST over a catchment. This also informs suitable areas for schemes that encourage enhanced infiltration losses (e.g. HOST class 2) and address areas with greater runoff problems (e.g. HOST class 20).
Rivers Ecological Status 2015 (Cycle 2) - WFD	Environment Agency	OGL	Displayed derivation data, WFD Ecological classification status of the river waterbodies. This indicates the target watercourses for addressing diffuse runoff issues from agricultural land.

Rivers Chemical Status 2015 (Cycle 2) – WFD	Environment Agency	OGL	Displayed derivation data, WFD Chemical classification status of the river waterbodies This indicates the target watercourses for addressing diffuse runoff issues from agricultural land.
Rivers Overall Status Time Series (Cycle 2) – 2013: 15 WFD	Environment Agency	OGL	Displayed derivation data, WFD Overall classification status of the river waterbodies. This indicates the target watercourses for addressing diffuse runoff issues from agricultural land and changes over time/land use.
Diffuse Source – WFD	Environment Agency	OGL	Displayed derivation data, shows the number of Tier 1 reasons for failure (diffuse source) for each river. This indicates the watercourse most affected by diffuse agricultural runoff issues, and possible schemes.
Tier 1 Reasons for Failure – WFD data	Environment Agency	OGL	Displayed derivation data, shows reasons for failure (invasive non-native species) reported for each river. This indicates the key reasons for failure and where to address diffuse pollution from agricultural land.
Significant Water Management Issues – Tier 1 – WFD	Environment Agency	OGL	Displayed derivation data, shows the proportion of different Tier 1 reasons for failure for each waterbody. As above, but graphically displayed to show other reasons for failure and the proportion of diffuse pollution.
SAGIS % improvement needed to meet WQS – P	Environment Agency	OGL	Displayed derivation data, shows the % improvement needed to meet current and proposed WQS for P. Source apportionment GIS (SAGIS) identifies the % of land altered to address water quality source of phosphorous.
SAGIS Opportunity for Catchment Management – P	Environment Agency	OGL	Displayed derivation data, if % improvement < 50 and diffuse P > 0.5 catchment management deemed possible. The same data used as above, but mined to indicate feasibility of addressing P with catchment management.
SAGIS Phosphorous Inputs	Environment Agency	OGL	Displayed derivation data, shows the proportion of phosphorus inputs from key point and diffuse sources. The same data used as above, but mined to indicate the different sources of phosphorous.
Risk of Flooding from Surface Water (3.3%, 1% and 0.1%AEP)	Environment Agency	OGL	Pluvial flood outlines to multiple return periods, to identify overland flow routes and extents. This informs the events to which a scheme is designed and most suitable interventions, e.g. runoff attenuation applied to steep overland flow pathways. This data also displays the current exposure of properties and businesses.
Risk of Flooding from Rivers and Sea (High, Medium, Low)	Environment Agency	OGL	Fluvial flood outlines and risk bandings, to identify out of bank flows and influence of existing defences. This data also displays the current exposure of properties and businesses.
Historic Land Cover (1906 – 1935)	Dudley Stamp	Conditional - not published	Historic land cover, pre-war time intensification to identify areas of potential restoration. For example, to identify historic hedgerow margins removed to enlarged arable fields for larger machinery and upscale farm economies, or 'cattle dip' ponds infilled when pasture farms became arable.

Land Cover (LCM2015)	CEH	Conditional - not published	Current land cover, identify spatial land cover and hydraulic surface roughness patterns. This informs priorities for addressing high runoff in low roughness fields (arable and improved grassland), and suitable schemes. Furthermore, constraints (urban areas/roads/railways) can be identified and screened out.
Habitat Action Plans (HAPs)	JNCC	OGL	Displayed derivation data, shows the target areas for particular habitats/species (e.g. wetland generation). This data also informs constraints/sensitivities, such as woodland planting in target areas for calcareous grassland.
Cotswold AONB Landscape Strategies	Cotswold AONB	OGL	Displayed derivation data, identified 19 different landscape character types in the Cotswolds AONB, used to inform decisions about the suitability of NFRM schemes within the Cotswold landscape strategy. For example, areas designated as an Unwooded Vale (LCT:19) would not be suitable for afforestation.
Living Landscapes	Wildlife Trust	OGL	Living Landscapes are designations where wildlife habitats are aimed to be larger, improved management and joined up, for example connecting woodlands to generate wildlife corridors. Schemes that detrimentally effect an existing living landscape (e.g. removing a hedge in place of a bund) would be unsuitable, however, schemes that enhance the living landscape (e.g. generation of wetland habitat) would be an opportunity.
Priority Habitat Inventory	Natural England	OGL	This spatial dataset designates the locations and extents of the Natural Environment and Rural Communities Act (2006) Section 41 habitats of ‘principal importance’. This catalogue of area data replaces the previous separate BAP habitat inventories collated by Natural England. Constraints and sensitivities considered when degrading priority habitats, but opportunities available if improving.
National Forest Inventory	Forestry Commission	OGL	An area dataset based on the NFI (2016) definition of a woodland, which is a “minimum area of 0.5 ha under stands of trees with, or with the potential to achieve, tree crown cover of more than 20% of the ground.” Saplings that are considered likely achieve a greater than 20% canopy cover is also mapped as woodland. There is also a width designation for woodland based on a minimum of 20 m, however, where woodlands are linked by a narrow stretch of trees < 20 m wide, the break may be omitted. These areas identify opportunities for wet woodland generation and/or utilising riparian timber for leaky debris dams.
England Habitat Network	Natural England	OGL	In addition to LCM2007, the England Habitat Network identifies four distinct habitats: a) Woodlands – broadleaved mixed woodland, broadleaved deciduous woodland, open birch woodland and scrub; b) Grasslands – rough calcareous grassland, rough acid grassland and rough neutral grassland; c) Heathlands –

			open dwarf shrub heath, dense dwarf shrub heath and bog, d) Mires, fens and bogs – bog, swamp, fen/marsh and fen/willow. Each habitat will provide constraints, sensitivities and opportunities based on the NFRM opportunities. For example, areas of calcareous grassland would be a constraint for afforestation, however, could be an opportunity for reduced stocking and grazing if used for pasture.
Sites of Special Scientific Interest (SSSIs)	Natural England	OGL	Natural England designated sites for a special interest by reason of any of its flora, fauna, physiographical and/or geological features. These sites can be considered a constraint or opportunity depending on scheme. For example, wading habitat is not suitable for afforestation but could be an opportunity for further surface water attenuation features e.g. offline storage and ponds.
Special Protected Areas (SPAs)	Natural England	OGL	Special Protected Areas (SPAs) are protected sites in accordance with the European Commission's Birds Directive (1979) Article 4, classified for vulnerable and rare birds (defined in Annex I), and for migratory species. These areas are constraints, sensitivities or opportunities, for example, felling trees to form leaky barriers would be an unfeasible for these areas, but afforestation that provides habitat would be an opportunity.
Special Area of Conservation (SACs)	Natural England	OGL	Special Areas of Conservation (SACs) are protected sites designated under Article 3 of the European Commission's Habitats Directive. These areas are constraints, sensitivities or opportunities. For example, mosses contain a high surface water level generating a rare habitat type; afforestation would not be suitable in areas of mosses as this would reduce the water available for the existing vegetation. However, additional storage by means of grip blocking would be an opportunity enhancing the habitat.
Existing Stewardship (ELS/HLS/OELS/CSS)	Natural England	Conditional - not published	Existing areas under rural payment agency (RPA) agreements are areas of constraints and sensitivities. For example, pollen margins that are altered to form offline storage would be in breach of the stewardship agreement and therefore generate a permanent ineligible feature (PIF) that could involve retrospective fines to the start of the agreement.
Targeted Stewardship (CSS)	Natural England	OGL	Countryside Stewardship replaces Environmental Stewardship as the Tier II payment under the Common Agricultural Policy for environmental betterment. Within the stewardship these are designated in tiers (Mid and Higher) based upon the capital items. These spatially targeted items inform opportunities farmers and landowners may want to consider for payment under a renewed stewardship agreement.

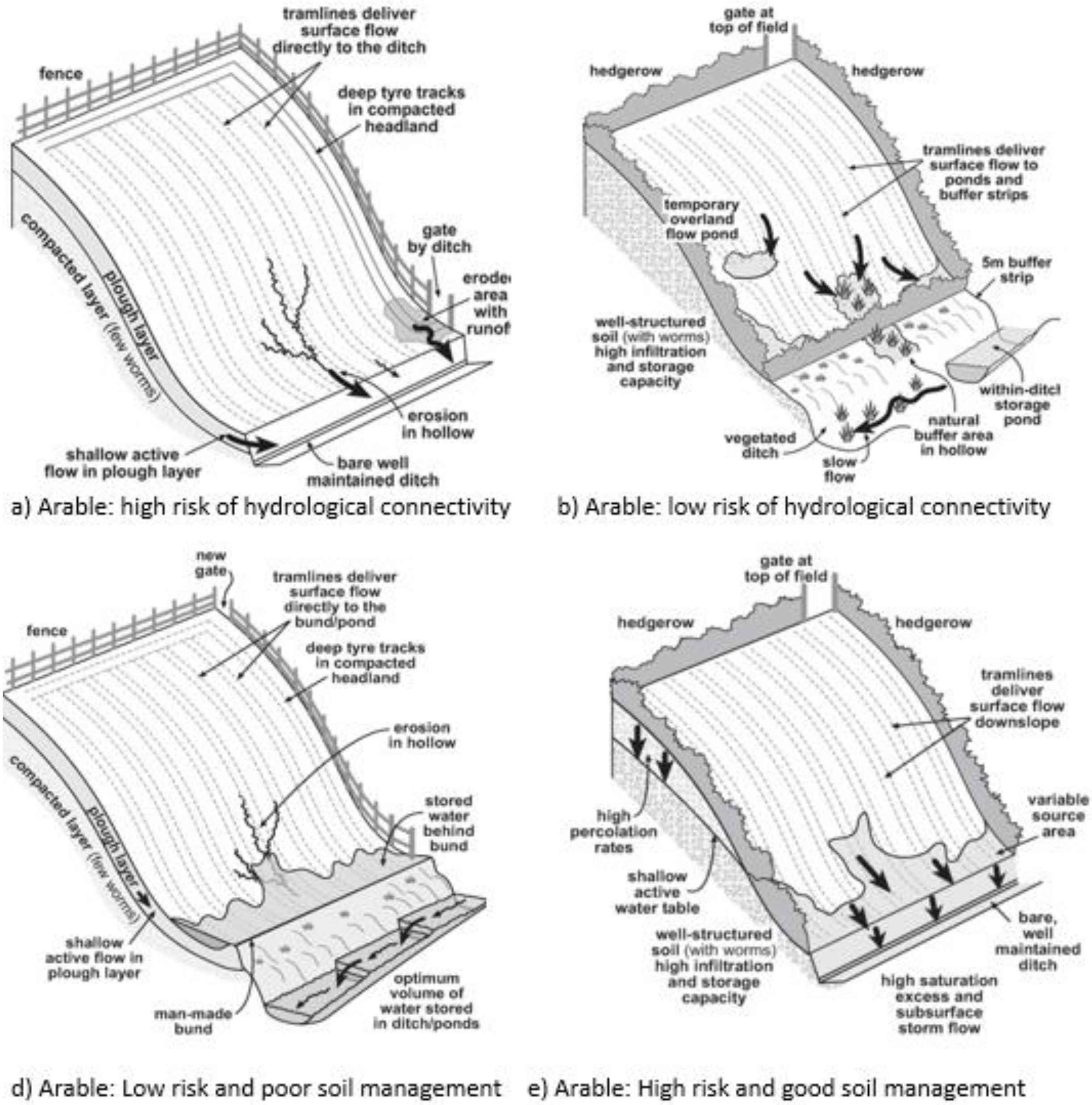
Rural Payment Agency Land Boundaries	Natural England	Conditional - not published	Background mapping, displayed land boundaries informs engagement/stakeholders across the catchment, including contact details identified in the layer attributes table.
Agricultural Land Classification (ALC)	Natural England	OGL	The Agricultural Land Classification (ALC) area data provides area designations based on a farms physical or chemical characteristics in relation to its agricultural use. High value land (Grade 1 and 2) are considered constraints and sensitivities to NFRM due to the high productivity associated with these areas, whereas medium - low grade (3 to 5) are opportunities due to the lack of agricultural use.
Standard Average Annual Rainfall (SAAR)	CEH	Conditional - not published	Displayed derivation data, average annual rainfall in the standard period (1961-1990) in millimetres.
Keeping Rivers Cool	Environment Agency	OGL	These areas are designated based on a four year (2012-2016) Environment Agency initiative. The Keeping Rivers Cool initiative focused on climate change adaptation for targeting riparian areas that could use trees to keep rivers cool. Displayed layer to indicate priority areas and opportunities for riparian afforestation.
Spatial Defence Layer with Attributes	Environment Agency	OGL	Spatial Flood defences layer shows the location and extent of flood defences currently owned, managed or inspected by the Environment Agency. This is a constraint layer to indicate areas of existing defences.

3.3.1 Applied WwNP Tools and Screening Datasets

In addition to the data sourced, mined and mapped to undertake desk-based characterisation (section 3.4), inform the PGIS exercise (section 3.5) and performance modelling (section 3.6), existing tools were applied to assist various elements of the NFRM scheme's co-design phases. The tools and how they have been applied are discussed in table 3.2.1 (see chapter 2.5 for a review of all existing tools).

Table 3.2 Existing Decision Support Tools (DSTs) and Decision Support Matrixes (DSMs) used in PGIS approach

Tool	Application
The Floods and Agricultural Risk Matrix (FARM) (Wilkinson, Quinn and Hewett 2013)	Unlike other location specific tools and datasets, the FARM tool provided a conceptual representation of the functions of applying NFRM principles on agricultural land. The schematics were used in the PGIS early engagement phase to indicate on-farm hydrological connectivity. However, the FIRM tools were not applied to the farms due to the lack of NFRM schemes applied as part of the recommendations. Furthermore, the tool lacked the ability to incorporate local knowledge (e.g. when overland flows became active) in order to refine a PGIS-NFRM scheme.
Sensitive Catchment Integrated Modelling Platform (SCIMAP) – Diffuse Pollution Risk Mapping Tool (Reaney *et al.* 2013)	A location specific mapping tool provided an indication of hydrological connectivity to illustrate the propensity of land cells (at $5m^2$) to generate runoff issues, with associated pollutants (e.g. sediment and phosphates). The downloaded layer was used to engage stakeholders in identifying whether their farms/holdings would generate runoff and connect to receiving watercourses. This enabled the clarification of CSAs and hydrological connectivity routes. However, unlike the RoFfSW dataset, this does not provide an indication of likelihood (AEP).



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f) Pasture: High risk and poor soil management g) Pasture: Low risk and good soil management

Figure 3.3 FARM schematics of arable and pasture, high and low, hydrological connectivity farms (Wilkinson et al. 2013 – sourced from FARM tool).

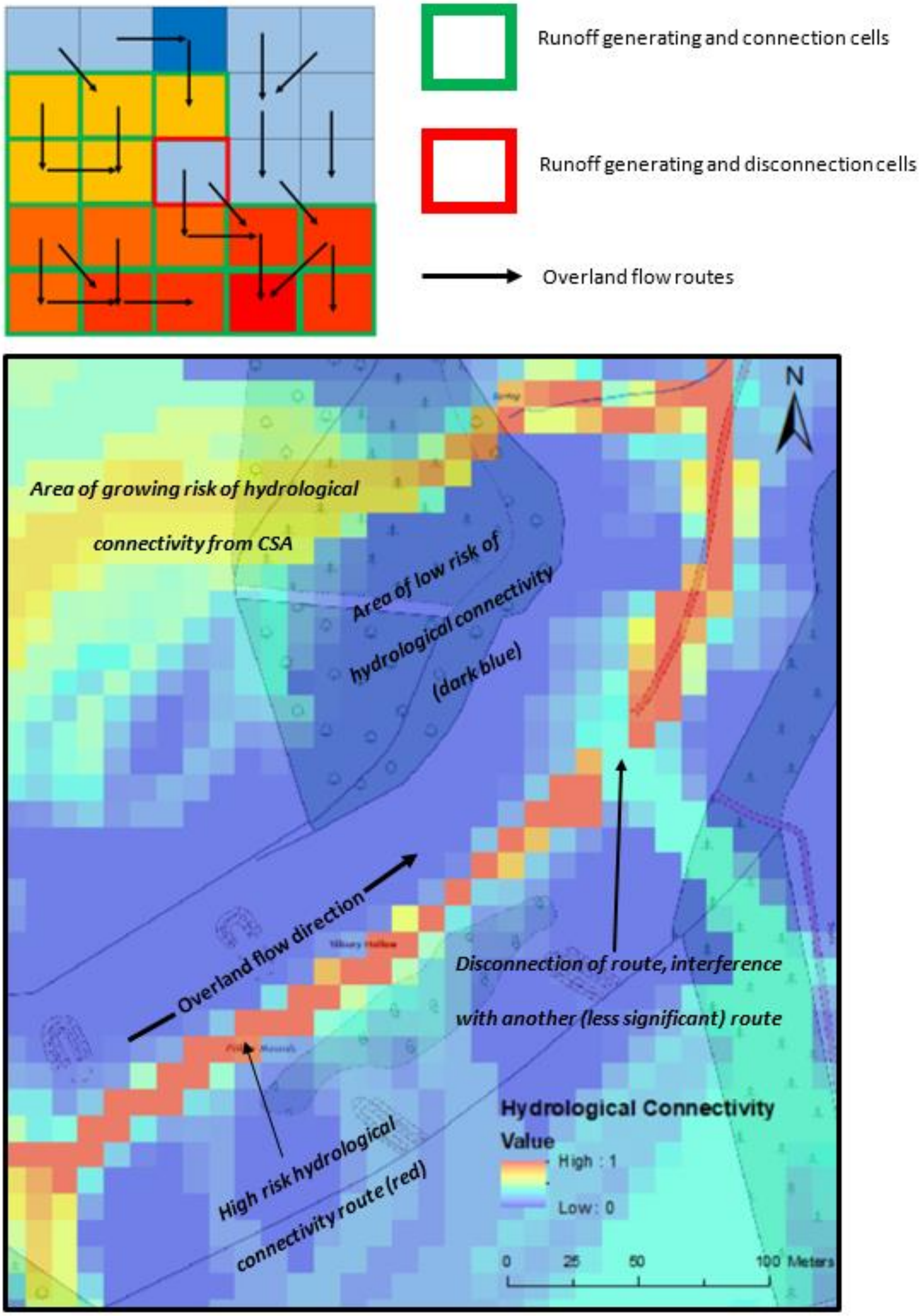


Figure 3.4 SCIMAP example, and the network index approach to hydrological connectivity

3.4 Research Catchment Description

The approaches used are those that could be applied to most rural, large, dendritic fluvial-based catchments (not influenced by tidal inundation), with fluvial and pluvial NFRM opportunities considered and co-designed. The Stour valley headwaters of the Warwickshire-Avon (Rural), West-Midlands, UK, was used as the study site (see Figure 3.5). The catchment extent is 187 km^2 and consists of four major sub-catchments, in order of size: Knee Brook (82 km^2); River Stour (60 km^2); Nethercote Brook (34km^2); and Pig Brook (6km^2). Each of these sub-catchments have further minor delineations that are contributed to from groundwater and overland flow sources, and are particularly diverse in terms of topography, land-cover, pedology, geology and ecology (identified when delivering the first aim). Figure 3.6 provides an overview of the catchment with corresponding tributary codes for future reference. There are several reasons why this catchment was chosen as a case study site:

1) The area was inundated by flooding in 2007, and subsequently every other year, with the most recent internal flooding of properties occurring March 2016 (Warwickshire County Council 2017).
2) Whilst most properties in fluvial flood zones are located downstream, there are also properties at risk in the headwaters, making this NFRM approach spatially complex. This requires the NFRM scheme to reduce risk downstream whilst not enhancing risk to upstream communities via backwater effects or peak synchronisation. Furthermore, this scheme will explore the role of cumulative benefits when hydrological up-scaling is used to counter dilution effects.
3) The high number of contributing delineations across the whole catchment represent different runoff generation patterns and levels of contribution that will be analysed in more detail; prioritising CBFM with the use of spatially targeted NFRM techniques.
4) The dominant agricultural land-use is pertinent both physically and politically. As discussed in chapter 2.2.3, arable intensification has been considered by many hydrologists to have detrimental impacts on the natural ability of rivers to manage high flows and sediment transportation (Oudin *et al.* 2008). This has informed an international and national political agenda

(e.g. Efra 2016 and Defra 2009a) that seeks to adopt methods of managing rural environments to alleviate flood risk by WwNP in a more holistic catchment based approach with NFRM schemes.

5) Capita Symmonds (2008) found after the 2007 floods that a 'do nothing' scenario was the only financially feasible option for Shipston-on-Stour (the furthest downstream community at risk within the study site). This was based on reductionist analysis of the event's storm flow, in which in excess of 166,790m^3 was required to be removed from the hydrograph and therefore was considered unfeasible based on flood defence grant-in-aid (FDGiA) economic appraisals. Whilst this sort of analysis applies to conventional flood storage areas (FSAs), it does not apply to the hydrological principles of catchment based NFRM that seeks to distribute the storm flow across the hydrograph, increasing the time-to-peak (Tp) to ultimately lower the flood peak (Qp) and rate of recession.

In terms of key policy agendas in the catchment area, long-term strategies are considered critical to increase at risk communities' resilience to the impacts of climate change (Environment Agency 2009). As outlined in the Warwickshire-Avon Catchment Management Plan (Environment Agency 2016b), the low-lying undulating hills and long history of frequent flooding to small and dispersed settlements has not aided traditional flood defence schemes, and requires a need to reduce flood risk by considering resilience and new adaptation methods. The study site is located in the Warwickshire-Avon Rural Operational Catchment boundary (see Figure 3.3), where 68% of waterbodies are reportedly failing to meet good ecological status under the Water Framework Directive – this has increased from 10 to 23 waterbodies at poor ecological status in four years (2009 – 2013), predominately thought to be the result of diffuse agricultural pollution sources (Environment Agency 2017d). The European Floods Directive (EU 2007) also advocates an integrated approach to catchment management, working with local stakeholders and natural processes wherever possible to address flood risk at the catchment scale (more information on policy agendas in chapter 2.3). The ability to utilise local gatekeepers in the form of a local flood action group, Natural England (NE) and the National Farmers Union (NFU) also enabled access to local farmers who could participate in the PGIS scoping study (section 3.5).

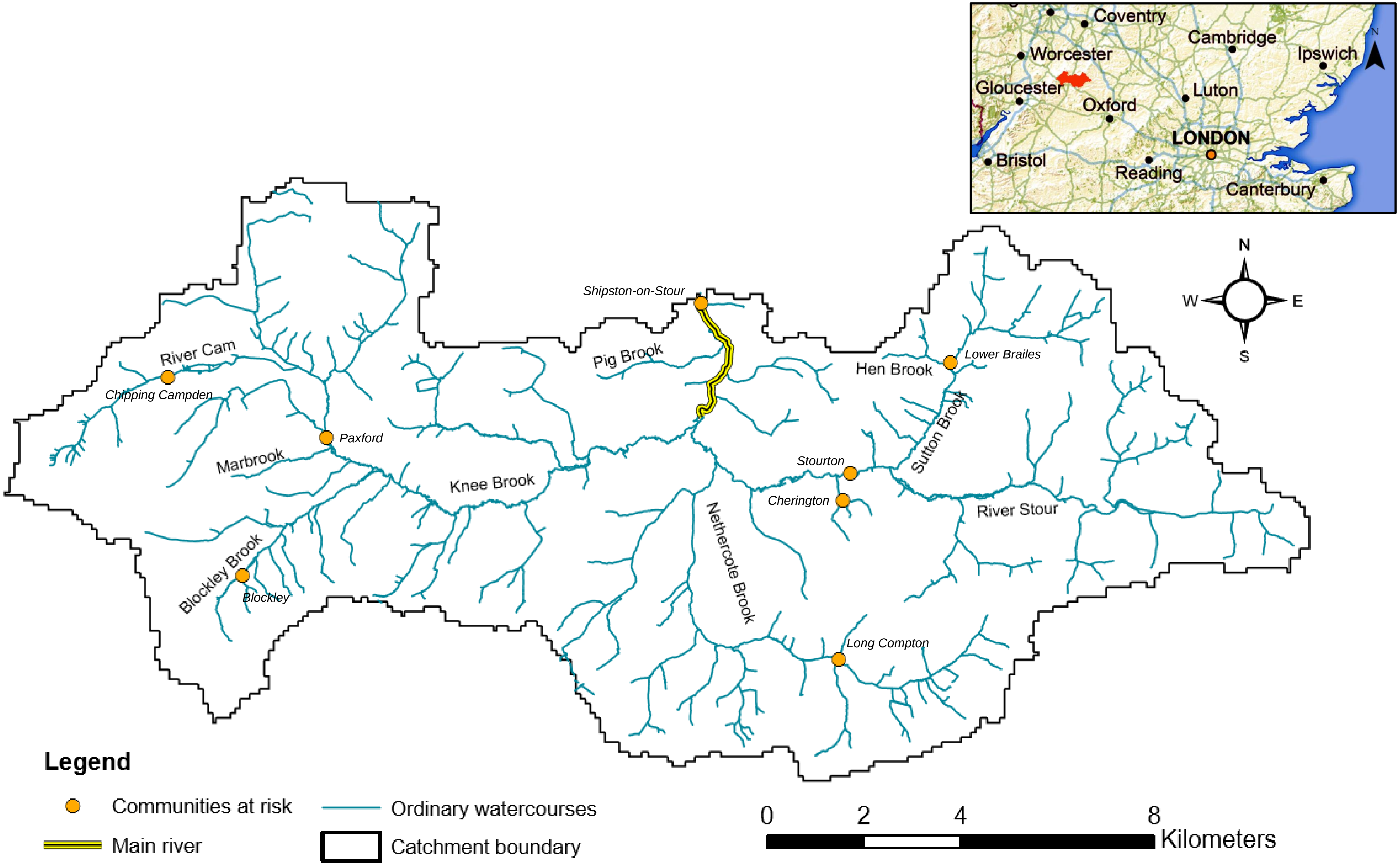


Figure 3.5 Catchment summary and location (Data Sourced: OS National Overview and OS 1:250000 scale data)

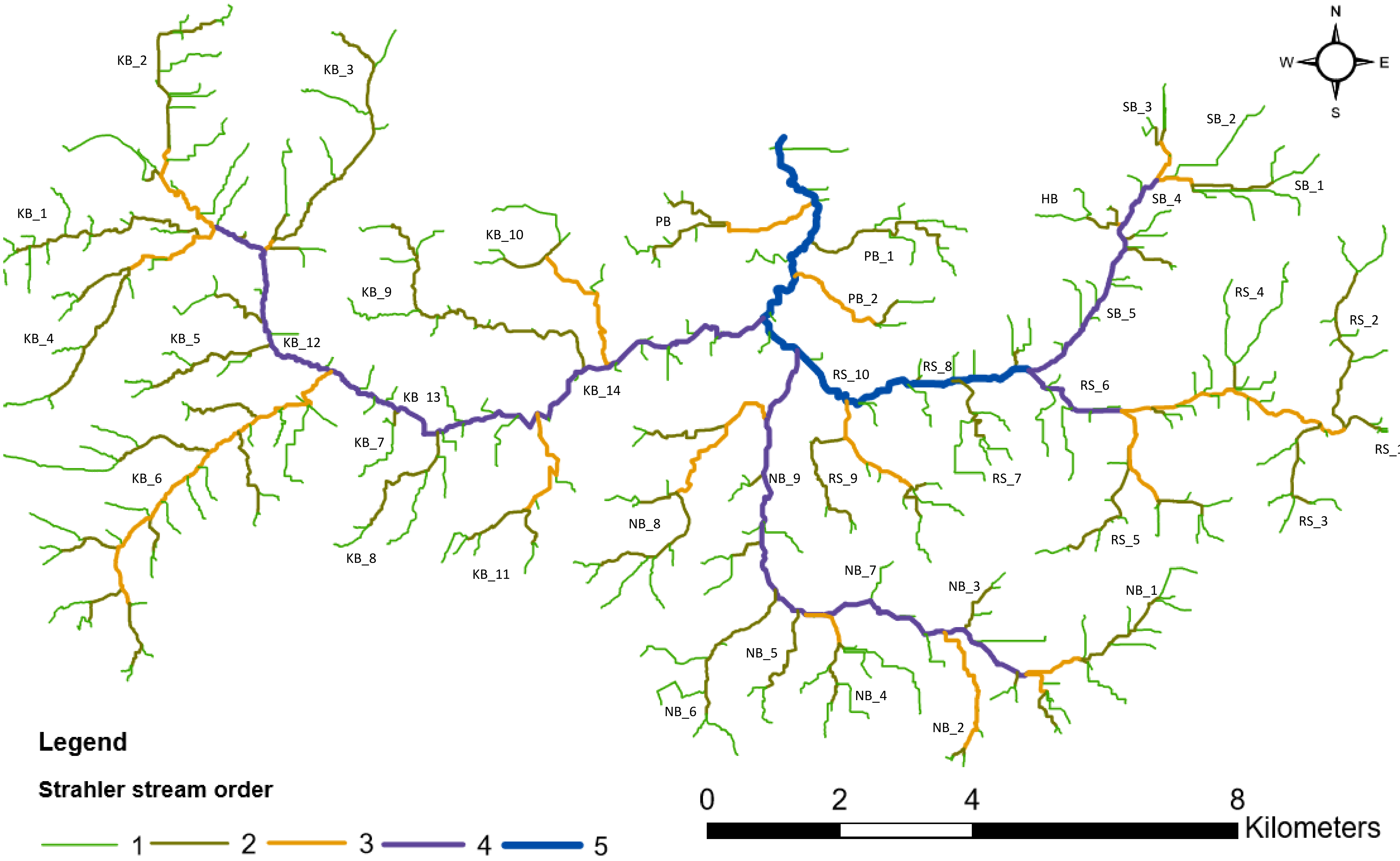


Figure 3.6 Strahler stream ordering, delineating catchment from low order (1) to high order (5) streams. Streams of the lowest order are considered the headwaters of the total catchment extent (Strahler 1957). These orders have been further delineated for reference during PGIS data collection and analysis in Table 3.3 below.

Table 3.3 Delineated catchment streams, including areas of each sub-catchment and landowner/estate holding participant reference number

Stream number	Size (km²)	Participant Reference	Size (km²)	Participant Reference	Size (km²)	Participant Reference	Size (km²)	Participant Reference	Size (km²)	Participant Reference	Size (km²)	Participant Reference
	Knee Brook (KB)		Nethercote Brook (NB)		Sutton Brook (SB)		Hen Brook (HB)		River Stour (RS)		Pig Brook (PB)	
1	8.2	1	6.9	14 – 15	2.5	22 – 23	2.9	28	4.1	38	3.8	9 – 11 – 12
2	6.8	3	2.4	15	2	24			6.2	38 – 37	1	30
3	6.9	4	2.1	16	3.4	25 – 26			2.7	36	1.2	30 – 19
4	3.9	2	3.8	17 – 18	2.2	27 – 28			4.9	35 – 34		
5	2.4	2 – 5	2.2	19	4.8	28 – 29			6	34 – 28		
6	10.3	2 – 5	4	20					3	34 – 33 – 28		
7	4.3	5 – 6	1.8	16 – 19					2.1	32		
8	5.1	5 – 7	7.7	11 – 21					4.3	31		
9	12.5	8 – 9	3.1	19					3.6	34 – 19		
10	10.6	10 – 11							5.9	19		
11	4.8	5 – 8										
12	2.5	5										
13	2	8 - 12										
14	2.4	11 – 12 – 13										

3.4.1 Geology

The Stour Valley's topography reflects the bedrock geology, with a permeable Inferior Oolite limestone in the upland headwaters and escarpments, particularly to the eastern extent (Knee Brook tributary) of the catchment - see Figure 3.7. The porous limestone transitions into more Lias grouped mudstone, silts and clay dominated bedrock in the lowlands and northern extent of the catchment with a less permeable valley bottom. The steeps valleys also descend into flatter valley floors as the Stour valley geology reduces permeability into the lower gradients of valleys floodplains. Erosional incisions within the porous limestone have been formed within the headwaters low order streams that penetrate and drain into the underlying less permeable Lias beds, establishing limestone spring draining from the uplands.

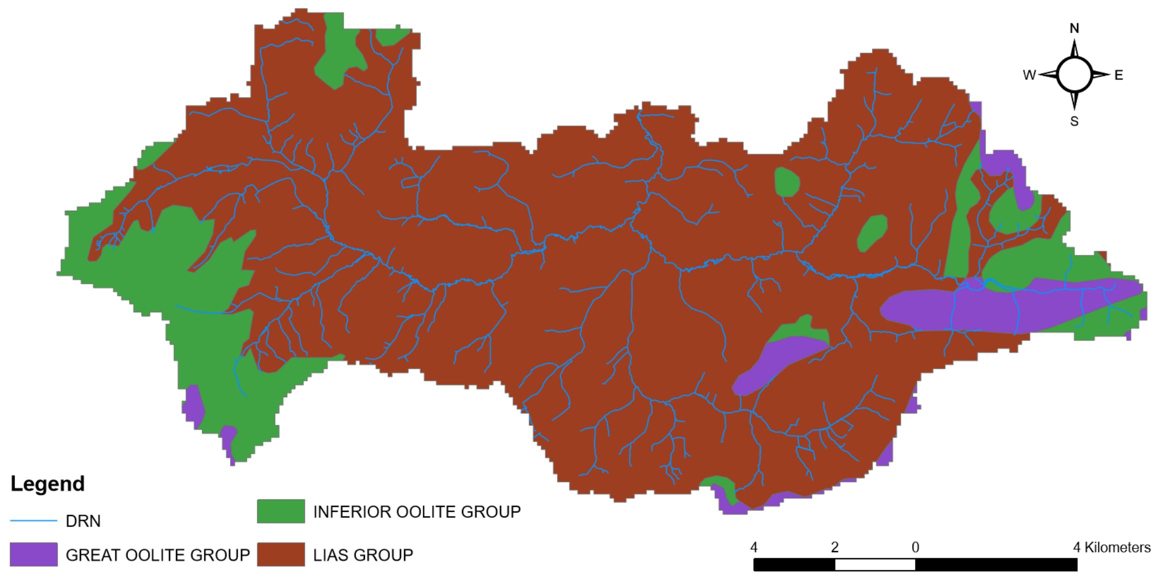


Figure 3.7 Geological characteristics across the study site (Data Sourced: BGS 2016)

3.4.2 Pedology

The pedology of the Stour Valley catchment reflects the underlying geological permeability, with a porous upland headwaters as defined by HOST class 2 (free draining over limestone, also known as 'brashy'), particularly the headwaters of the Knee Brook and Nethercote Brook, see Figure 3.8. This then transitions into more gleying impermeable clays in the lowlands and extensive floodplains as defined by HOST classes 24 and 25, with the greatest catchment coverage. The soil characteristics indicate a low propensity for infiltration and limited storage capacity within the soil in the lowlands of the catchment, and more spring-fed highly productive aquifers and a capacity to infiltrate within the headlands. In the headwaters of the Knee Brook, HOST class 20 indicates a small percentage of slowly permeable clay with limited storage capacity. The smallest coverage is attributed to HOST class 5: free draining permeable soil in unconsolidated sands and gravels with relatively high permeability, as in the lowlands of the Nethercote Brook sub-catchment.

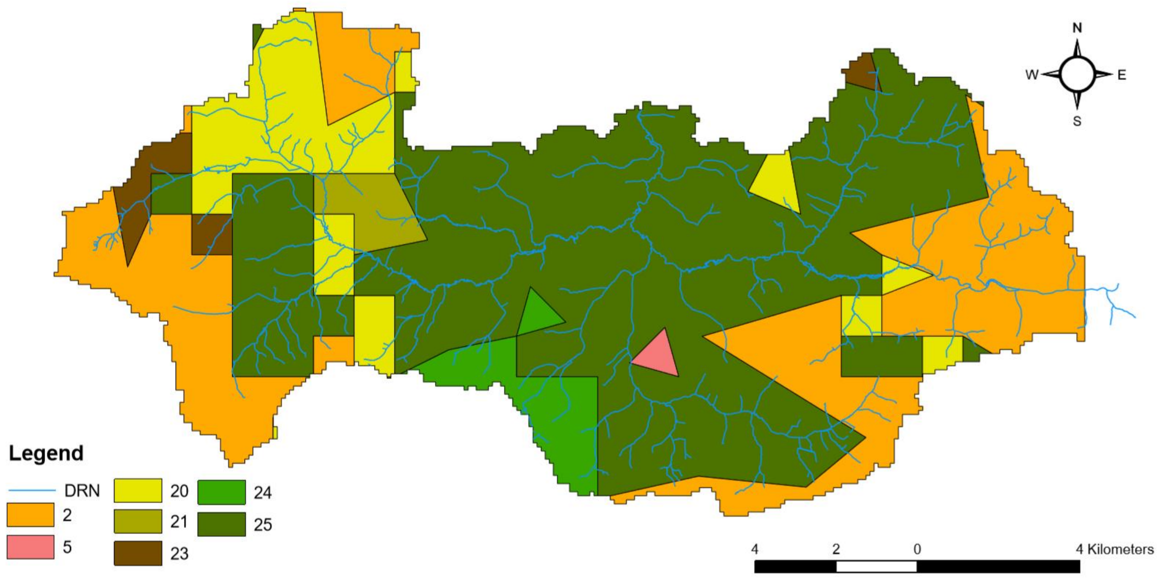


Figure 3.8 Pedological characteristics of the study site (Data Sourced: CEH 2016)

3.4.3 Current Land Cover

The land cover of the Stour Valley catchment has been determine by the CEH Land Cover Map (LCM) 2015 dataset (outlined in section 3.3, presented in Figure 3.9). The greatest land coverage is attributed to arable and horticultural land (42%) and improved grassland for predominately livestock purposes (37%), outlined in Figure 3.9. Woodland and rough grassland accounted for the smallest coverage across the total study site, 12.2% and 13.5% respectively. The land cover characteristics vary further across sub-catchments, with the Knee Brook containing the largest percentage of woodland (15.3%) and rough grassland (14.6%) in comparison to the other delineations; whilst the River Stour had the least woodland and rough grassland, 11.2% and 10.5% respectively. Based on LCM2015 data, areas unsuitable for all NFRM techniques (built up areas and gardens, and inland rock) accounted for 12.1% of the total study site.

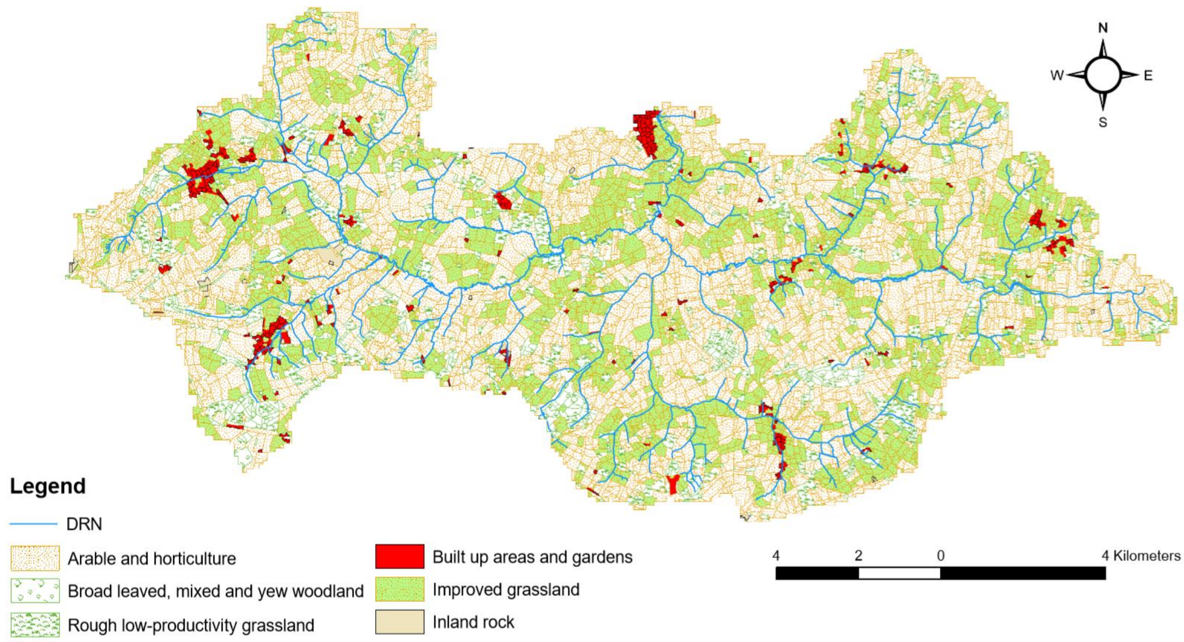


Figure 3.9 Current land cover characteristics of the study site (Data Sourced: CEH 2016)

3.4.4 Elevation

The Digital Terrain Model (DTM) of the Stour Valley presented in Figure 3.10, was generated using LiDAR 2m composite tiles from 2017 to obtain a bare-earth representation of the catchment surface that does not contain elevation returns for trees, buildings and general infrastructure. There is a 247.43m change in elevation from the uplands to the furthest downstream extent (Shipston-on-Stour), with the highest point of elevation located at the headwaters of the Knee Brook (305.51 mAOD). The lowlands contain expansive floodplains in the valley floor, between 103.2 – 60 mAOD. The DTM indicates a dendritic basin with many high order tributary feeds across the sub-catchments. Erosional incisions into the limestone have shaped steep and eroded valleys that feed into the receiving watercourses, many of which are used in conjunction with farm drainage practices.

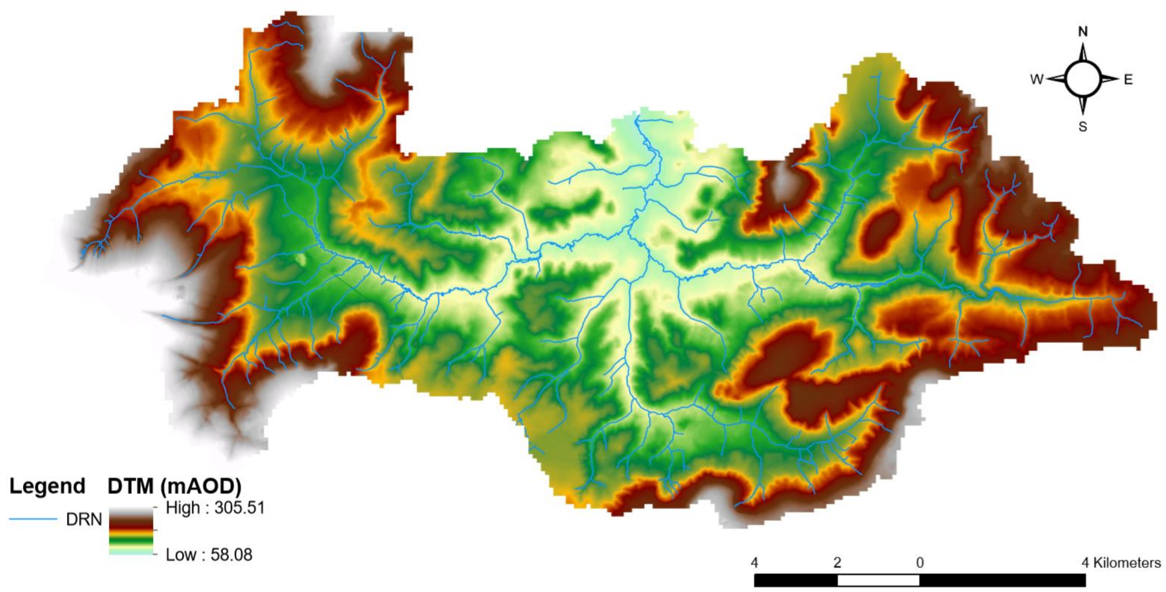


Figure 3.10 DTM of study site using 2m resolution LiDAR (Data Sourced: Environment Agency 2017e)

3.4.5 Water Quality

The ecological status of the Stour Valley catchment was identified using the latest available cycle of recorded sampling data (2013 – 2015) that is associated with individual EA waterbody classifications. Displayed in Figure 3.11, all watercourses failed the WFD targets of meetings 'good' ecological status, primarily due to diffuse pollution from agricultural land management sources (Environment Agency 2017d). The Nethercote Brook (WB_ID - GB109054039820) has the worst water quality of the total catchment area with a 'Poor' designation. Macrophytes are forecast to stay 'Poor' by 2021 and 'Moderate' by 2027 due to the time associated with ecological recovery, however, this is based on modelling general trends in catchment status as opposed to forecast interventions and monitoring. In Nethercote Brook, much like the rest of the catchment, phosphate and sediment levels is the result of agricultural land use diffuse sources.

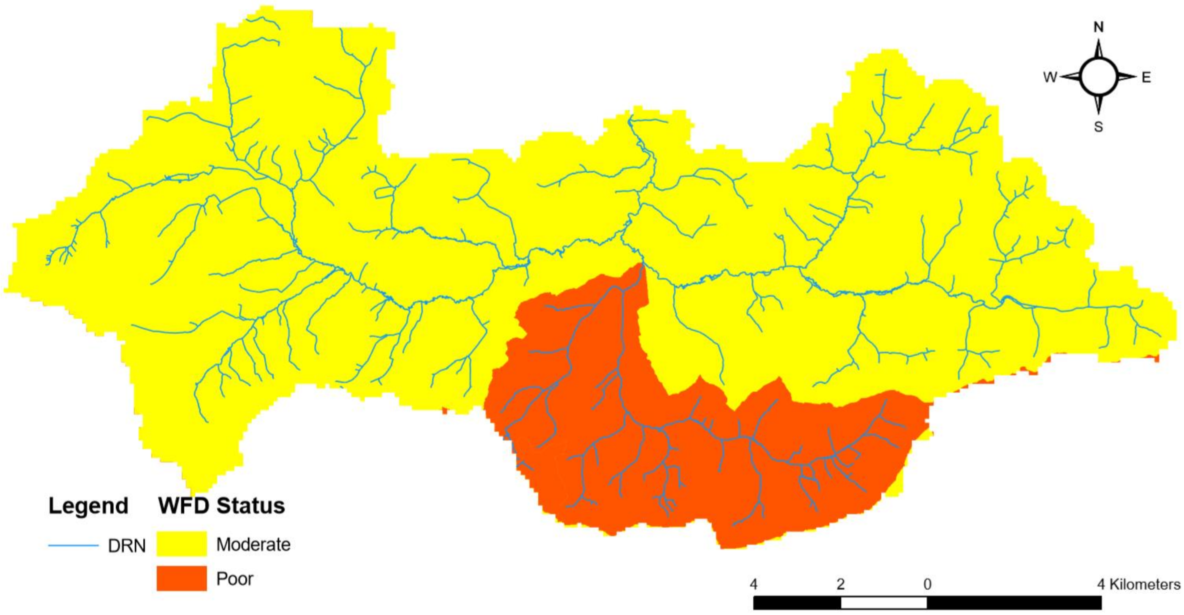


Figure 3.11 WFD status of study site (Environment Agency 2017d)

3.4.6 Rainfall

According to CEH Met Office Standard Average Annual Rainfall (SAAR) at 5km^2 grids, rainfall totals vary considerably across the catchment area. The highest rainfall totals (721 – 796mm) occur in the headwaters of Knee Brook, in the south westerly extent of the catchment. The lowest rainfall is estimated in the lowest reaches of the catchment, as well as headwaters of the Sutton and Hen Brooks. Most rainfall was associated with the Knee Brook and the west extent of the catchment more generally, with an average of 682 – 720mm of rainfall estimated across this region. Whilst rainfall does not indicate river response and therefore contribution to downstream flood risk, it can be considered that the spasmodic rainfall pattern outlined in Figure 3.12 indicates the Knee Brook (and any NFRM techniques applied there) will have to respond to greater (yearly) rainfall totals.

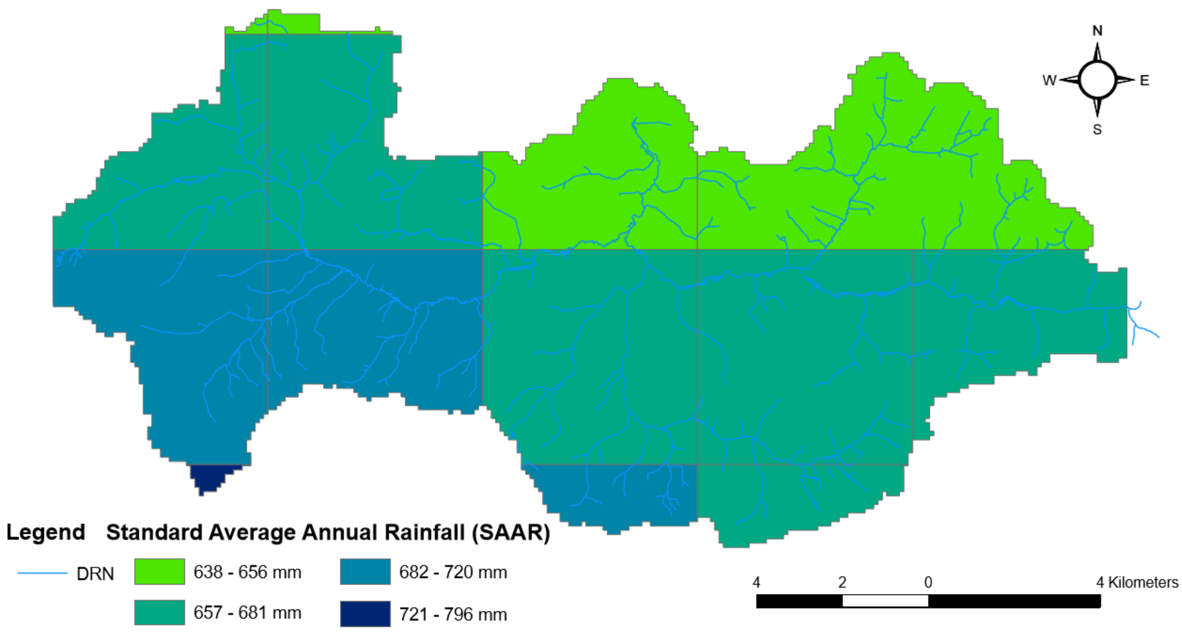


Figure 3.12 Spasmodic rainfall grids across the study site (Met Office 2016)

3.4.7 Risk of Flooding from Surface Water

The Risk of Flooding from Surface Water (RoFSW) extent layer indicates a high number of sources of pathways of flood waters across the study site. Surface water (pluvial) flooding occurs during saturation-excess overland flows. These extents account for where water flows and ponds based on topography and storms for different return periods (3.3%AEP, 1%AEP and 0.1%AEP) applied across the study site as a mesh-based rainfall grid model (more information provided in section 3.3). It is important to note that whilst the flood extents (particularly 1%AEP and 0.1%AEP) intersect many properties and businesses, these models cannot be used to indicate the risk to individual properties and businesses due to the lack of further detailed modelling that considers other influential parameters such as defences (Environment Agency 2017a).

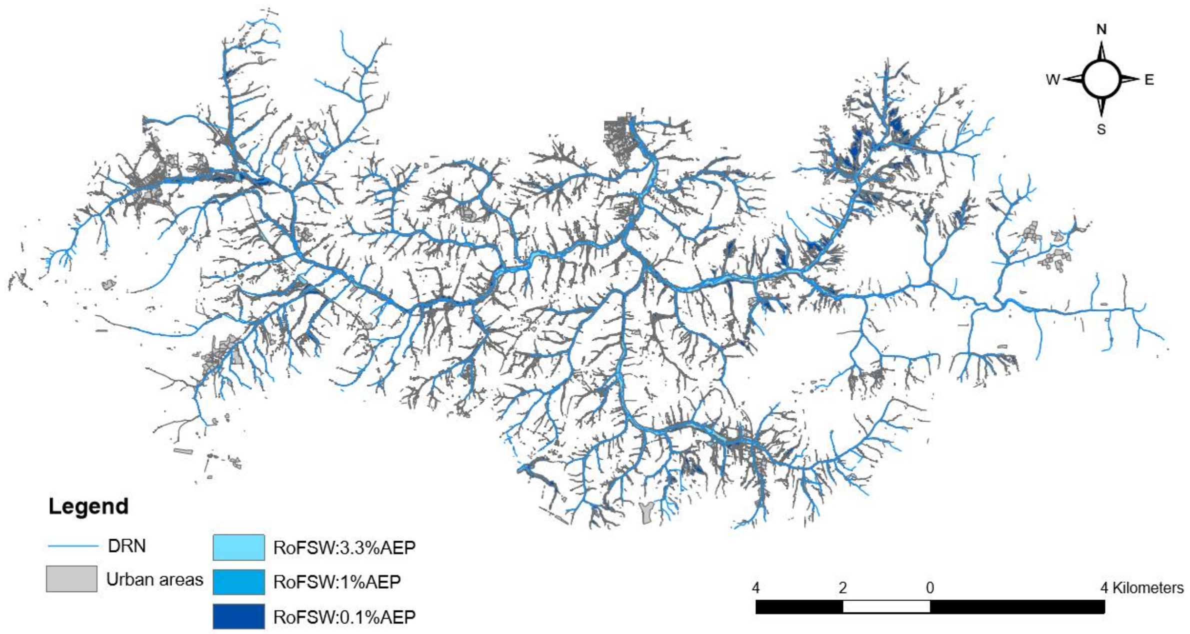


Figure 3.13 Risk of Flooding from Surface Water extents across study site (Environment Agency 2017a)

3.4.8 Risk of Flooding from Rivers

The Risk of Flooding from Rivers and Sea (RoFR&S) extent layer (previously known as National Flood Risk Assessment (NaFRA) Spatial Flood Likelihood Category Grids) indicates larger floodplain connectivity in the Knee Brook and downstream Stour extent, compared the Sutton Brook, River Stour and Nethercote Brook. The flood extents shows the likelihood of each 50m cell within the floodplain from rivers becoming inundated. Four flood risk categories (High – Very Low) are allocated to each cell, taking into account flood defences and their condition, providing a more realistic dataset for indicating the risk from different return periods from rivers (Environment Agency 2017b). These categories relate to the following return periods:

- High risk: > 3.3%AEP
- Medium risk: between 1%AEP – 3.3%AEP
- Low Risk: 0.1%AEP – 1%AEP
- Very Low Risk: < 0.1%AEP (no cells within the floodplain were considered to be very low risk)

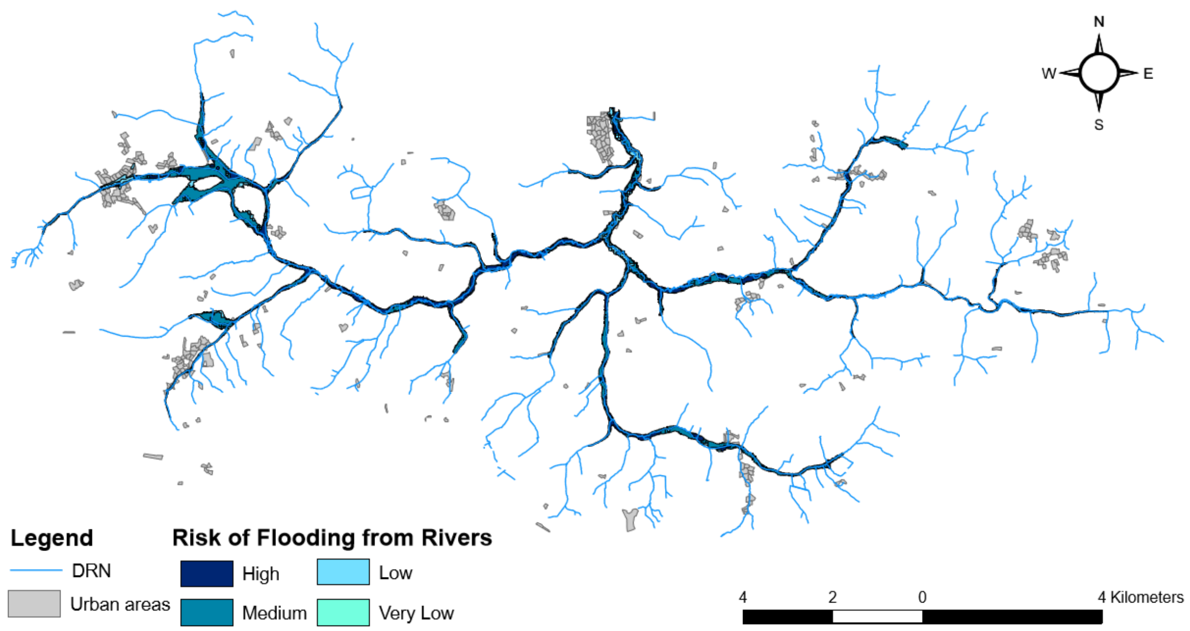


Figure 3.14 Risk of Flooding from Rivers extents across study site (Environment Agency 2017b)

3.4.9 Agricultural Land Classification

The Agricultural Land Classification (ALC) dataset is based on a classification system used in England and Wales to spatially grade the quality of land for agricultural use, according to the physical or chemical characteristics. These classes are based on Grade 1 (excellent quality) to Grade 6 (very poor quality), outlined in Figure 3.15. The climate (temperature, rainfall and aspect), soil characteristics (structure, depth and chemical properties), and fluvial and coastal flood risk is also weighted to determine the associated ALC characteristics. Only 4.3% of the study site was characterised as Grade 1 agricultural land in the headwaters of the Knee Brook. Grade 1 ALC is widely considered a constraint for NFRM opportunities due to the high economic gains associated with conventional crop growth (SEPA 2013 and Hankin *et al.* 2018) The majority (72.6%) of the catchment was characterised as Grade 3 (moderate) ALC with moderate limitations that affect the crop choice and level of yield. The Grade 3 land areas are considered to produce moderate/high yields for a few crops or moderate yields of a wide variety of crops. Low grade ALCs (4 – 6) are commonly considered the most favourable for NFRM techniques, however, this only accounts for 17.2% of the study site, primarily within the floodplains.

Figure 3.15 Agricultural Land Classifications (ALC) across study site (Natural England 2016)

3.4.10 Sites of Special Scientific Interest (SSSIs)

Sites of Special Scientific Interest (SSSIs) are designated by Natural England, as those areas of land and water that represent natural heritage in relation to at least one of the following factors: flora, fauna, geology and geomorphology. These sites are considered constraints for NFRM opportunities due to the risk of degrading the condition of the SSSI's 'carrying capacity', known as the ability of the site to sustain and respond to any proposed alterations (Natural England 2017). Figure 3.16 outlines all SSSIs across the study site, the largest of which - Wolford Wood and Old Covert - is situated in the Nethercote Brook sub-catchment. The second largest SSSI, Whichford Wood, is situated in the headwaters of the River Stour tributaries. In total, SSSIs only account for 4.7% of the total catchment area, the majority of which is accounted for by Wolford Wood and Old Covert (2.5%) and Whichford Wood (1.9%). Based on recommendations from previous scoping studies (SEPA 2013 and Hankin *et al.* 2018), SSSIs will not be considered in the opportunity mapping phase of research and have been screened out of any co-design engagement work (further discussed in section 3.5).

Figure 3.16 SSSIs across the study site (Natural England 2016)

3.4.11 Social Characteristics: Catchment Boundaries, Ownership and Land Use

Across the useable 143km^2 of the 187km^2 total catchment area (based on constraints and sensitivities mapping outlined in section 3.3), there were 129 participants of the PGIS framework. Figure 3.17 outlines the coverage of engagement participants, including the pilot farm (reviewed in chapter 4) with 38 farmers and landowners engaged as key decision-makers and a wider 91 consultees including drainage contractors, game keepers, farm/estate managers, family members and tenant farmers of land owned but not farmed by the landowner, to provide their input and advice on opportunities, as outlined in Figure 3.18. In some instances, tenants, farm managers and estate managers were key decision-makers and would consult the landowner. As discussed further in section 3.5, unlike other NFRM scoping studies, this research sought to collaborate with farmers and landowners to co-design NFRM opportunities on the basis of what is acceptable to these key stakeholders. Therefore, recording cadastral boundaries enabled an understanding of the varied level of participation with the influence of participant characteristics on identified NFRM opportunities.

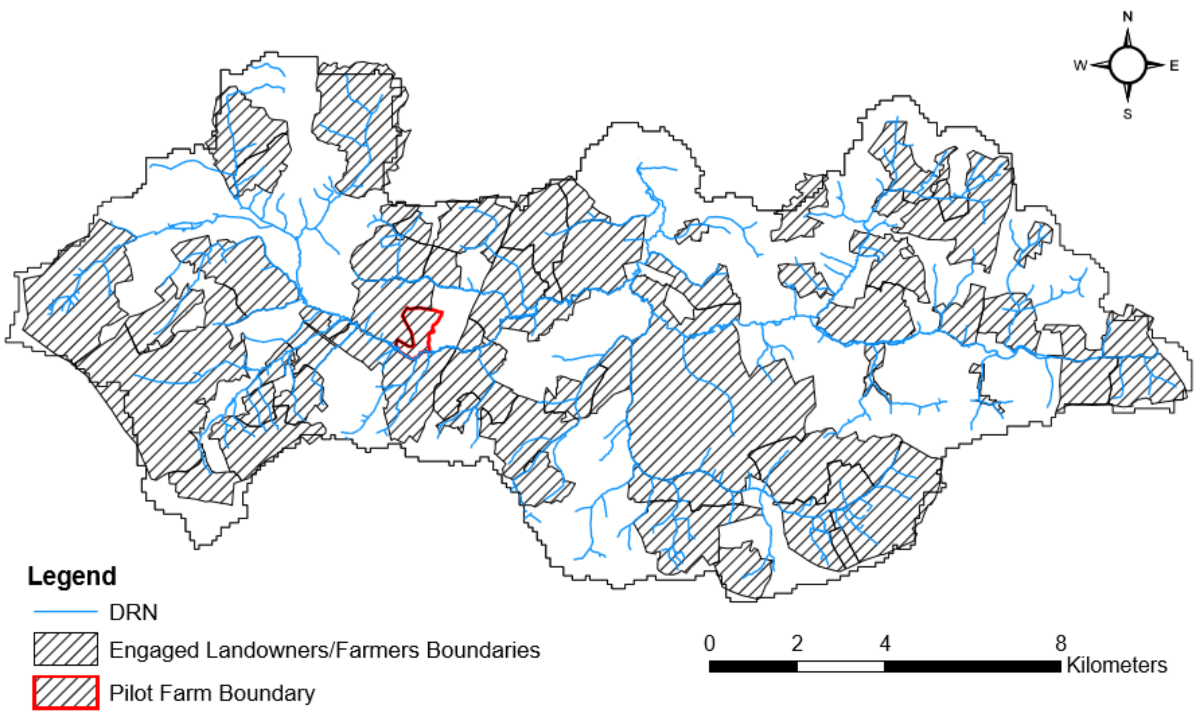


Figure 3.17 Extent of landowner and farmer engagement during the PGIS exercise. 44km^2 outside of these boundaries are those designated as areas of NFRM constraints (such as urban areas, etc. outlined in section 3.3).

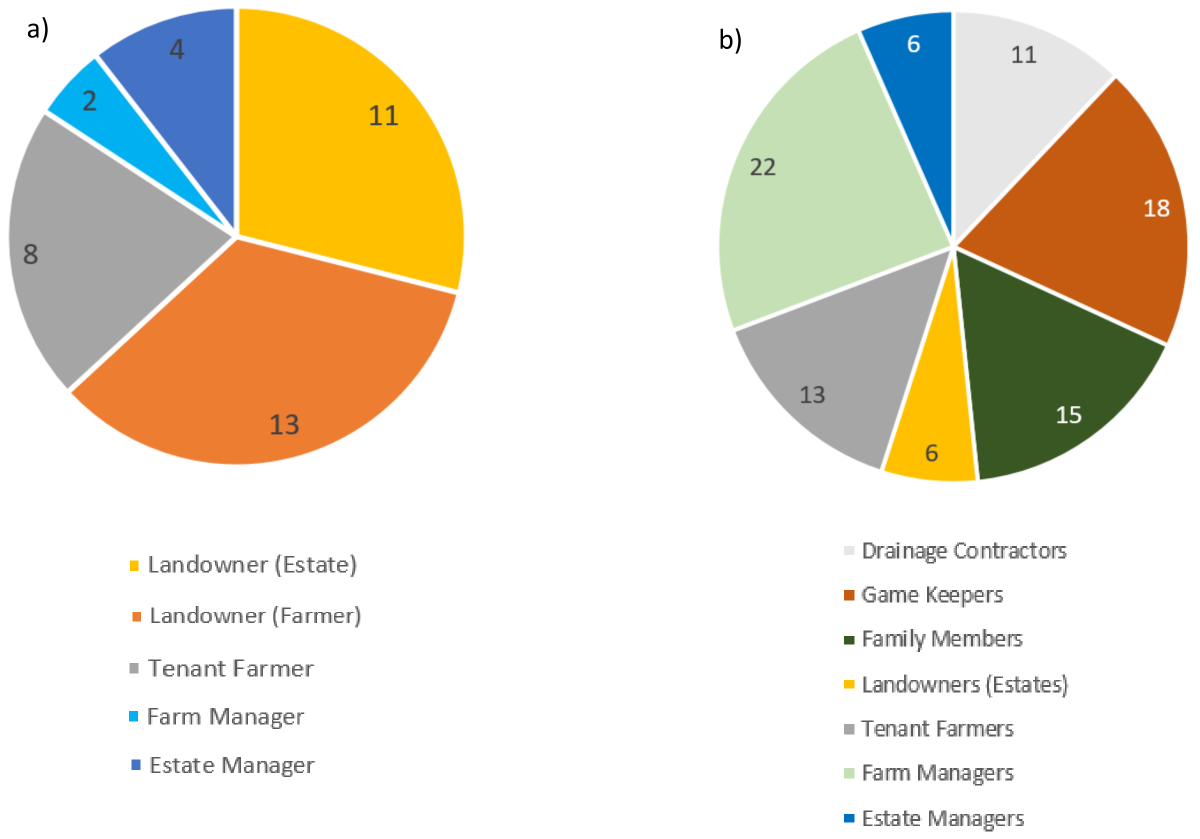


Figure 3.18 Participant classifications, a) key-decision makers and, b) wider-consultees

Table 3.4 highlights the differences in cadastral coverage between the sub-catchment delineations. Whilst there are no studies into land ownership patterns and NFRM opportunities, Bark, Martin-Ortega and Waylean (2017) reflected from a farmer engagement workshop that any NFRM adoption is highly dependent on the financial constraints and short-term returns needed by tenant farmers. The NFUs 'flooding manifesto' also identified a crucial need to support tenants undertaking NFRM schemes who may require more financial support to invest in the capital costs and long-term maintenance of any structure (NFU 2017). Land under tenure is also considered to have greater legal complexities when situating NFRM, where landowners and tenants would require joint-approval under the tenancy agreements containing pre-existing conditions that must be retained in any NFRM scheme. This pattern was identified during PGIS exercises with 76% of tenant farmers who also consulted their farms landowner.

Table 3.4 Cadastral differences across catchment area (percentage coverage). Urban areas and land managed by public bodies, principally SSSIs (Natural England) not included, designated constraints

	Land owning farmers/estates (% cover)	Tenant Farmers (% cover)	Difference (%)
Knee Brook	76	24	52
Nethercote Brook	86	14	72
River Stour	77	23	54
Sutton Brook	80	20	60
Pig Brook	81	19	62
Average (%)	80	20	60
Total catchment (%)	77.4	22.6	54.8

Participants were also classified based on their dominant land use practices (outlined in Table 3.5), as attributed by the landowner and/or farmer. Land use is a social classification of how the land is used by the landowner and/or tenant for each holding (38 in total). This differs to land cover, for example, an area can been classified as 'improved grassland' based on LCM2015 data but may not be *used* for livestock purposes. The dominant land use type by area coverage of the 'useable' catchment was sheep livestock, with 29% designated across 143km^2, equating to 41.47km^2. Cereal crop cultivation equated to 26% land use coverage (37.18km^2) and recreational estates (commonly for game shooting) comprised 23.6% coverage (33.75km^2). Areas designated for forestry and conservation land use comprised the smallest coverage at 12km^2 and 9.6km^2 retrospectively. This indicates a limited area set-aside for woodlands and wider environmental betterment. The next section (3.5) covers the Participatory GIS (PGIS), opportunity mapping phase of the research, co-producing an understanding of the flood risk problems across the catchment before co-designing NFRM opportunities.

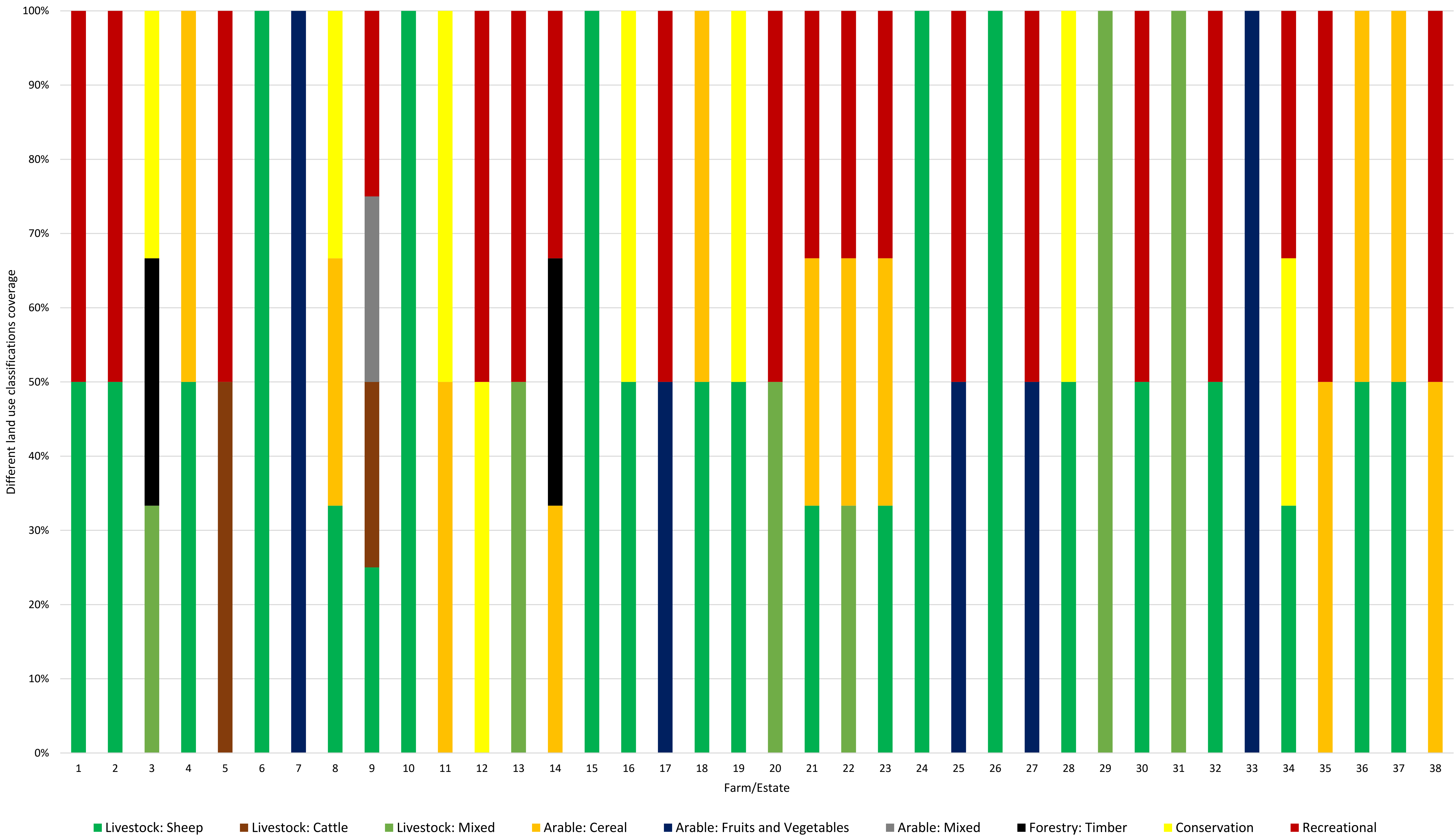


Figure 3.19 Participant land use classifications, as attributed by the farmer and/or landowner in reference to the key rural and agricultural land use classifications in MAFF (1998).

3.5 Opportunity Mapping: Participatory GIS

The Participatory Geographic Information Systems (PGIS) Opportunity Mapping element of the assessment, relating to the second aim of identifying NFRM potential across the study site, is widely recognised as a basis to inform the exploration of catchment-based schemes (Whitman *et al.* 2015). SEPA (2013) and the Environment Agency (Hankin *et al.* 2017b, Burgess-Gamble *et al.* 2018) recommend the collation, mining and analysis of influential data (outlined in section 3.3 and 3.4) to produce maps that physically, hydrologically and socially characterise the catchment area, as well as identifying possible sensitivities and constraints on where measures cannot be implemented (e.g. existing open waterbodies, urban areas, roads, ministry of defence land etc.) in order to underpin decision-making about what features could be installed where. In this project, the desk based mapping exercise (provided in section 3.4) has been supplemented with participatory approaches that enabled the active engagement with landowners and farmers about where to prioritise NFRM. This process was undertaken for individual farmers and landowners across the catchment using Rural Payments Agency (RPA) files to outline cadastral boundaries and details. This approach made the participatory engagement process more site sensitive, engaging individuals and obtaining local knowledge.

Due to the size of the study site (187 km^2) and the large number of upstream tributary contributions, some initial watershed analysis in ArcMap using the hydrology tools was undertaken to delineate all contributions in the first aim, including sub-catchment tributaries, ditches and areas of high levels of runoff (also known as discretisation of the catchment (Metcalfe *et al.* 2017)). A number of tools have been employed to identify 'problem areas' suitable for different NFRM features (Reaney *et al.* 2016, Djodjic *et al.* 2018). However, it was recognised that more detailed local assessments were required to devise a comprehensive understanding of individual sub-field scale assessments of flooding sources, pathways and receptors in order to digitise a realistic, catchment-scale, NFRM scheme (Doak 2008). This section will outline the PGIS framework, detailing the process of validating, communicating and analysing data (Forrester and Cinderby 2012). Chapter 4 outlines the process and outputs from a pilot study farm, with the purpose of testing the robustness and replicability of the method.

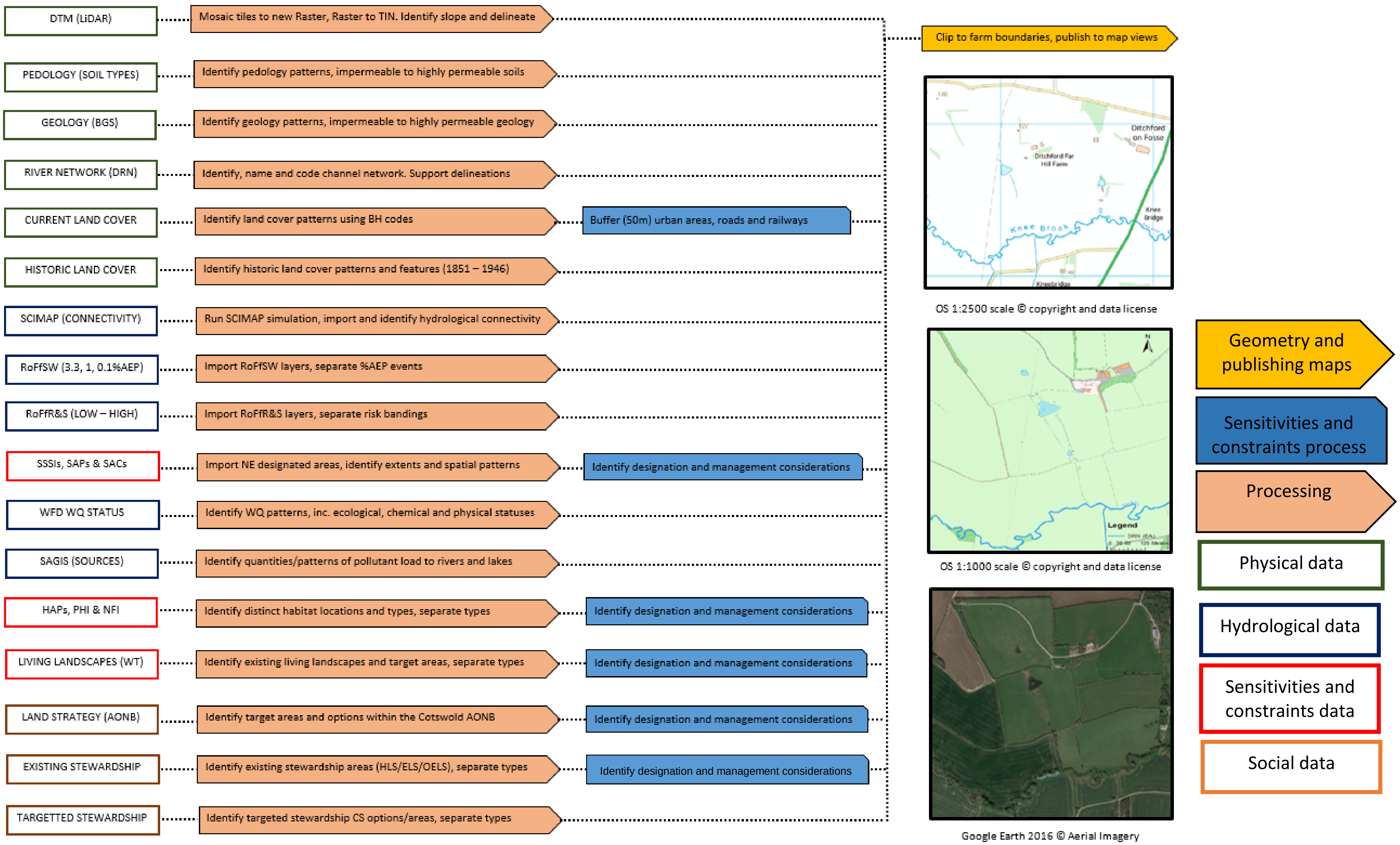


Figure 3.20 Processing data from field (<1km^2) to large catchment scale (>100km^2) in order to generate Farm Information Packs (FIPs) to apprise PGIS participants.

Figure 3.20 illustrates the base mapping process that generated the maps for individual farmers and landowners, and was provided in each farm and estate's Farm Information Pack (FIP) (provided in Appendix D, containing bespoke clipped maps with a guide to NFRM interventions in Appendix C), and facilitated the development of the PGIS-NFRM scenario. This section outlines the GIS frameworks used to co-design map based NFRM opportunities across the catchment. This was based upon a process of active engagement to merge existing scientific understanding (indicated in the FIPs) with local knowledge (the information provided by the landowners and farmers, and captured on maps). Lane *et al.* (2015) from Callon (1999) characterises three distinct models to engage stakeholders in flood risk science.

1) **Educating the public**, assuming there is a deficit in understanding flooding between 'experts' and 'lay' people, requiring top-down communication methods and intermediaries to relay complex hydrological processes to the public (Godfray *et al.* 2014, McEwen *et al.* 2015). This approach maintains a 'hierarchy of information' and lack of knowledge sharing (McEwen *et al.* 2017, Haughton *et al.* 2015) - an increasingly unpopular method of engagement in modern FRM practices, outlined in Chapter 3.2.5 (Defra 2017, Efra 2016), and an increasingly unfeasible method of obtaining landowner and farmer support in installing NFRM interventions (O'Connell *et al* 2010, Johnson 2017).

2) **Debating the public**, developed by Callon (1999), considers that those who have a stake in the decisions made should directly question 'expert' knowledge, enabling farmers and landowners to argue the validity of scientific findings and increase their cogency amongst stakeholders (Evans 2015). A classic example is the opening of Local Flood Risk Management Strategies (LFRMs) and Catchment Flood Management Plans (CFMPs) to public consultation. The consultation exercise enables agencies to formally take on board public knowledge. However, concerns regarding complexities in data and a lack of clarity in how 'experts' have calculated results (especially models) often leads to a lack of trust between the consultees (public) and agencies (experts) (White and Richards 2010).

3) **Active engagement** allows for a multi– (or two-) directional transfer of experiences and understanding (technical and local) to co-produce knowledge, enabling engagement to become a much earlier part of the research framework (Leadoux *et al.* 2003). The co-production of knowledge (Kindon *et al.* 2007) allows stakeholders to inform the research as opposed to scrutinising and debating findings when presented. Collins and Evans (2002) recognise that flood risk understanding can be influenced by experience-based expertise, informed by flood memories of how land and rivers respond to heavy rainfall (McEwen *et al.* 2012, Krauss 2012). Unlike passive engagement, active engagement aims to enable a continued discussion that includes inputs from both a local and technical understanding (Lane *et al.* 2015).

This research adopted the later model of active engagement via PGIS for individual farmer and landowner engagement in co-designing the modelled NFRM scenario, as well as providing site and experience-based expertise on historic flood events, extents and issues that can inform and question numerical model building and findings. By engaging only farmers and landowners individually, an historically underrepresented group in flood risk decision making (O'Connell *et al.* 2014, Holstead *et al* 2015) it supports the long term sustainability of any scheme adopted by these critical stakeholders by being involved in the choice and siting of the NFRM scheme (Reed *et al.* 2009).

In total, 38 farmer and landowners, and a further 91 consultees across the farms and estates were engaged on a one-to-one basis. Their sub-catchment location in the study site and land use indicators are displayed in Section 5.2 and Appendix E. After identifying all applicable landowners/farmers across the entirety of the catchment area using RPA land boundary data, their contact details where obtained using local gatekeepers including Natural England and a local resident flood action group, it was then possible to approach the participants via email, letters and phone calls to outline the project aims. Those landowners and farmers that were not identified by gatekeepers, were identified by neighbouring landowners and farmers who were participating in the research and able to make introductions, permitting a snowball sampling approach (Flynn 1973, Sampson *et al.* 2018).

Once landowners and farmers consented to participate and provided ethical approval (Appendix B), summary sheets of all river based NFRM techniques were sent prior the PGIS exercise (Appendix C). Three A3 sized base maps clipped to their holdings at 1:25000, 1:1000 scales and Google Earth aerial imagery were provided for annotations during the PGIS, along with characterisation maps and engagement tool outputs outlined in section 3.3.1 and Farm Information Packs (FIPs) (Appendix D). These physical, hydrological and social characteristics, as well as possible sensitivities and constraints were explained before the PGIS mapping exercise (taking 2-3 hours depending on the size of the farm/estate). Participants also undertook field walks with the maps to 'ground-truth' desk-based data with their own knowledge and considering the feasibility of any NFRM opportunities. These inputs from landowners and farmers enabled reviewing of the remote GIS data collated in meeting the first aim, with transparent communication of local knowledge through annotations in order to confirm a possible NFRM scenario (recommended by Cinderby 2017, Wilkinson *et al.* 2017). The PGIS process took a period of 14 months across 38 farms/estates, steps outlined in Table 3.5 and Figure 3.21.

Prior the commencement of the mapping exercise, the NFRM Guidance Document (Appendix C) was sent to the participants after obtaining their informed consent, outlining the aim of the project 'to identify opportunities to slow, store, disconnect and filter flood flows' (Wilkinson *et al.* 2012, Ngai *et al.* 2018). Summary sheets were also provided within the Guidance Document of all NFRM techniques, including runoff management, river and floodplain management and woodland management. During the PGIS mapping exercise, there were two key forms of local knowledge acquired: i) Flood memories were obtained during the PGIS exercise, gaining information of historic flood extents, ideally with some indication of depths (if possible); and ii) based on the understanding gained using FIPs and flood memories, NFRM opportunities were co-designed. The NFRM co-design process built on the co-production of knowledge around flood sources and pathways, which utilised the participants' local knowledge along with the desk-based catchment characterisation maps within the FIPs. Particular historic flood events, were also identified including the dates certain areas of land were inundated, either by overland and/or out-of-bank flows. Sources and pathways of flooding were also identified, including CSAs (i.e. those areas with a propensity to generate downstream and/or overland flows with a high hydrological connectivity to receiving watercourse; and/or downstream communities). This process informed the final co-designed NFRM opportunities that were based on the available options (outlined in Appendix C) and local tactile knowledge gathered, including, stewardship, arterial drainage and business considerations, to identify acceptable interventions to the participants. This includes identifying the specification and dimensions of the NFRM opportunities that is then digitised using reference shape and point files for each NFRM intervention.

Table 3.5 Key steps of co-designing NFRM opportunities

Step	Description
i. Introduction	Approaching landowners and farmers, following shared contact details and in some cases introductions by the gatekeepers (Natural England, local authority and local resident flood action group). Steps 1 – 2 in Figure 3.21.
ii. Project outline	Obtaining consent from landowners and farmers, signing participant consent forms to participate in the PGIS exercise and allow farms/estates flood risk contributions analysed. Steps 2 – 3 in Figure 3.21.
iii. Bespoke FIPs	Physical, hydrological and social characterisation maps per farm/estate. Step 4 in Figure 3.21
iv. Conducting PGIS exercise	Identifying sources and pathways of flood flows per farm and estate, supported by referenced years in flood memories in order to inform co-designed NFRM opportunities. Steps 5 – 10 in Figure 3.21.
v. NFRM confirmation	Confirming final co-designed NFRM opportunities, digitised in GIS outlining dimensions and capacities of each NFRM opportunity in precise locations. Step 11 in Figure 3.21

The full framework of co-designing NFRM opportunities is outlined in Figure 3.21, with the process tested in section 4 on a Pilot Farm Study Site with Participant 9 in Knee Brook, in order to test the robustness and replicability of the PGIS framework to be applied across the whole study site. Section 3.6 details the performance modelling (aim 3) of the research, specifying the data requirements, processes and parameters to test the performance of the co-designed NFRM opportunities.

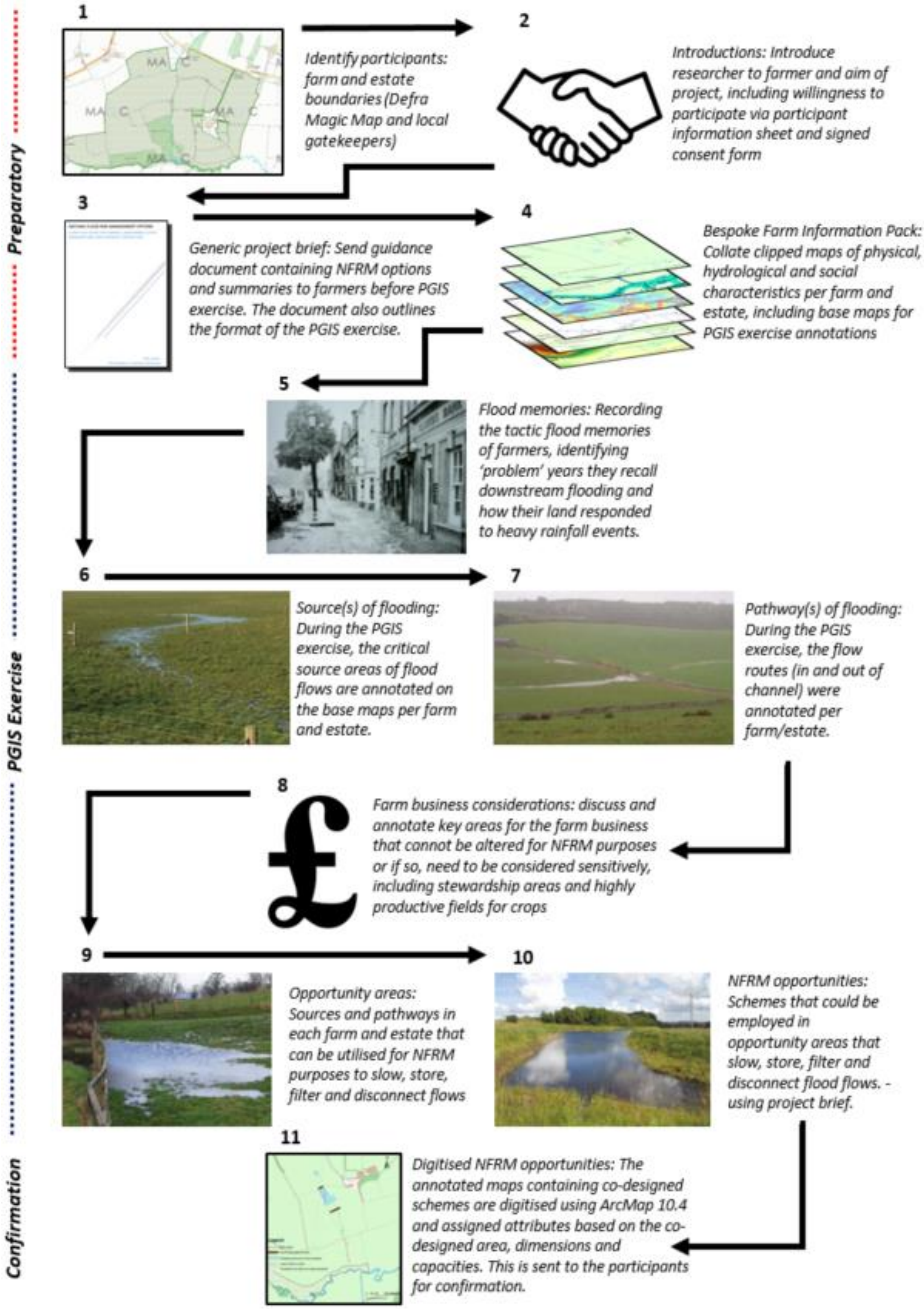


Figure 3.21 PGIS framework to co-design NFRM (meeting second aim)

3.6 NFRM Performance Modelling

3.6.1 Generic Approach

Following the PGIS-NFRM Opportunity Mapping exercise (objectives 2.1 - 2.4) discussed in section 3.4, with pilot results presented in section 4 and full catchment NFRM opportunities outlined section 5, it was recognised that understanding needed to be sought of the effectiveness of the proposed NFRM opportunities. This section describes the modelling methodological approach adopted in this thesis, including the analysis techniques to consider the metrics of NFRM performance to multiple flood risk scenarios including: peak convergence, attenuation and confidence in these outputs.

The overall approach used individually linked 1D/2D hydraulic models in xpswmm © and Flood Modeller Pro ©, interconnected by a 1D routing model where appropriate. Options were grouped based upon their spatial proximity, giving a total of 36 separate models based on the discretisation of the meso to local scale undertaken as part the catchment characterisation (first aim) In accordance with UK FRM, Evans (2014) recommended that it was required to appraise and manage the range of AEPs and consequences of flooding. This lead to the generalised 'Risk Assessment for Strategic Planning' (RASP) framework for quantifying flood and coastal erosion risks (Evans 2014, Environment Agency in press), which has been adopted in this modelling approach, informing a proportionate risk-based approach for targeting NFRM implementation in areas for greatest effect (DETR 2000, Environment Agency 2011a, Penning-Rowsell *et al.* 2016). In accordance with the RASP framework, this model is based on the guiding Flood Impact Modelling (FIM) principles (Nicholson 2013, Wilkinson *et al.* 2015 and Quinn *et al.* 2016), by routing multiple NFRM models it was possible to identify such areas of synchronisation and de-synchronisation through multi-scaled level analysis of the fluvial network and subsequent travel times of storm peaks, also known as flood-wave propagation, through the discretisation of the whole catchment area (Preissmann 1961, Heathwaite *et al.* 2005, Jackson *et al.* 2008, Metcalfe *et al.* 2016, Metcalfe *et al.* 2017, Dixon *et al.* 2017, Hankin *et al.* 2017, Anderson *et al.* 2006, Bennett *et al.* 2006, Beven 2012, Lamb *et al.* 2012, Park *et al.* 2009).

3.6.2 Model Structure

Here, the build of a numerical model for evaluating catchment flow regimes and the performance of NFRM is described. This section is to demonstrate the model is suitable for simulating FEH rainfall-runoff processes (discussed in section 3.6.3). The model was developed using data mapped and mined from the GIS catchment characterisation (in order to meet the first aim and outlined in section 3.4), including the DTM, watercourse network, delineations, land cover (LCM2015), infiltration (HOST) and background mapping (OS 1:1000 scale). This model was also calibrated against observed high flow data (NaRFA Station Number 54106), further discussed in section 3.6.4. The river models employed a link-node scheme (as applied for pipe networks), represented by trapezoidal/natural cross-sections determined from topographic DTM data within river reaches. It is important to recognise a number of rules in the model construct were made and adhered, outlined in Table 3.6 and Figure 3.22.

Table 3.6 Model build assumptions

Parameter	**Assumption**
FEH rainfall input	FEH events have limitations when disaggregated to reflect spasmodic rainfall. Without observed rainfall data across all sub-catchment there is some uncertainty in the Q inflows calculated, with homogenised inflow hydrographs based on catchment characteristics (FEH, volume 4) to represent heterogeneous rainfall-runoff patterns.
Channel geometry	The baseflow depth was artificially set as 1m across the entire catchment. Due to a lack of channel topographical survey data, and the DTMs not including bathymetry (water penetrating) stream bed levels, the 1D network was altered to include stream beds in channel geometry. This makes assumptions on any stream bed features.
Channel roughness	In the baseline scenarios, the entirety of the channel network was set as 'natural' hydraulic roughness value (0.035 Manning's n value). For the NFRM scenarios, this was altered to reflect different NFRM techniques, further discussed in section 3.6.5.
Infiltration rates	Assigned using HOST 1km^2 grids and associated look up table for differing classes. These were further homogenised to each sub-catchment model, assigning the infiltration rate with the most dominant HOST class. This was altered to reflect different NFRM techniques, further discussed in section 3.6.5.

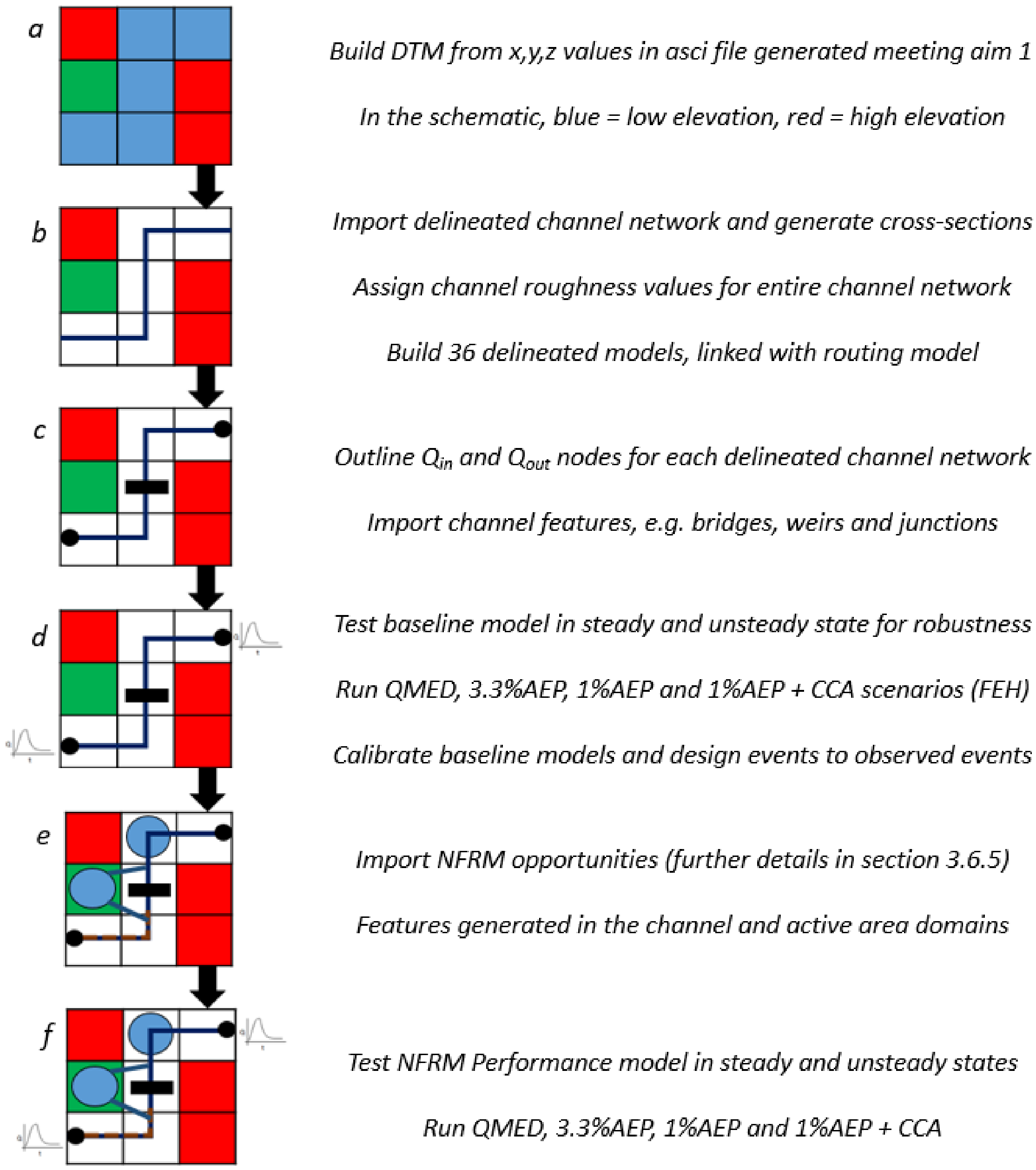


Figure 3.22 Modelling method schematic.

Figure 3.22 represents the process of building baseline and NFRM scenarios tested to multiple return periods. The features used to represent the NFRM opportunities have been developed using existing tools within the hydraulic model, further explained in section 3.6.5. Mass balance checks and sensitivity analysis of the parameters used within the baseline models are conducted between steps *d* and *e* to ensure the model is robust enough to be tested to multiple storms. The climate change allowance (CCA) for the model was based on Environment Agency (2019c) guidance from the UKCP18 (Met Office 2018) flow projections and set for +35% for the 2080s high central allowance for the SRBD.

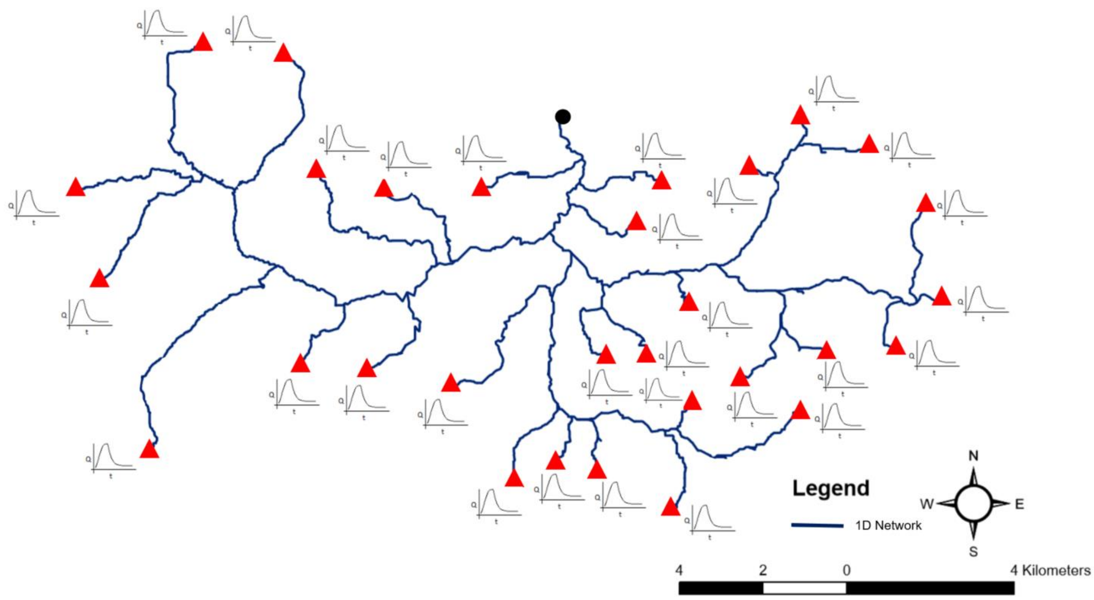


Figure 3.23 1D model network and Qin hydrograph locations across the study site

Figure 3.23 outlines the total model network (1D domain) and all FEH inflows across the study site, with the final outflow determining performance at the large (>100km^2) catchment scale at the observed river level gauge (station number 54106). It is likely that different locations within the study site that undergo NFRM will have variable effects experienced at the outlet. The reasons for the different effects at the catchment scale are threefold:

- Variable sources: Different catchment areas receive different rainfall patterns
- Variable pathways: Different catchment areas produce different amounts and types of runoff
- Variable pathways and receptors: Travel times and convergence (synchronicity) impacts as flood waves propagate through the network and converge with downstream delineations.

As outlined in section 2.2, flood risk can be reduced by means of limiting hazard, exposure and/or vulnerability (Lane 2017). This model scope focusses on NFRMs' capability to decrease the hazard, with the aim to reduce the rate with which channel stage (h) (levels) exceed a critical water stage (h_c) when flooding to properties and businesses occur. The hydrodynamic modelling can express the reduction of stage in the flowing representation of river discharge (Q) as the product of mean velocity (V), width (w), and mean depth, the latter of which is defined here as the difference between peak river stage and the mean channel bed level (z_b) and addition of h, shown in equations 3.1 and 3.2.

$$Q = wV(h - z_b)$$

Equation 3.1 Simplified representation of river discharge (Q)

Manipulation of the above equation defines stage as the product of three parameter groups.

$$h = Q\left(\frac{1}{wV}\right) + z_b$$

Equation 3.2 Simplified representation of river stage (h)

Equation 3.2 indicates river stage can be reduced through: i) measures that can locally increase channel width and/or flow velocity (e.g., removing meanders to increase a reaches carrying capacity and hence velocity), reducing the level of the river bed (z_b) (e.g., desilting and dredging) or building linear defences that effectively reduce h_c; or ii) manipulating the delivering rate at which water is conveyed from upstream sources via pathways to the receptors (areas at risk), reducing river discharge (*Q*). Conceptually, reducing Q implies activity upstream from the measured point modifying the flow through the basin. The basic principle that the model must represent is the ability of NFRM opportunities to holistically manipulate river discharge, temporally (at the flood peak) and spatially, upstream of at-risk settlements, for strategic targeting.

For the Shipston-on-Stour outlet and 36 delineated upstream sub-catchments, the FEH return periods have been generated using a 12hr critical storm duration for each of the delineations (outlined in section 3.6.3). The outlet hydrographs were then disaggregated using the sub-catchment hydrographs to the following downstream delineation. Therefore, the final outlet hydrographs of all delineation collated to create the outlet hydrograph in Shipston-on-Stour. Calibration along with mass balance checks and sensitivity analysis (outlined in section 3.6.6) has been used to ensure a stable and robust representation of the Stour Valley's processes with limited errors. The model user was then able to manipulate the delineations' Qp and Tp to investigate impacts at the downstream extent outlet as a result of the PGIS-NFRM opportunities across the study site.

To help improve the understanding between the interactions of different NFRM opportunities across the catchment, hydraulic modelling of the Stour Valley was undertaken using hydrodynamic flood models, validated in representing in-channel and floodplain hydraulics, essential when understanding whole catchment dynamics (Beven 1991, Shaw *et al.* 2012 and Hankin *et al.* 2016). Furthermore, the Environment Agency guidance on mapping and modelling catchment processes (Hankin *et al.* 2016) recognises the significance of understanding all fluvial flow regimes to inform a 'targeted' approach to NFRM, especially in terms of synchronisation and de-synchronisation at the meso-scale (Owen *et al.* 2016 and Environment Agency 2001).

Figure 3.24 Schematic of 1D/2D boundaries in model construct (Jacobs 2015)

Developing the recommendations of Rose *et al.* (2017) in the whole Eden catchment model methodology, an iterative approach to the model build was used, calibrating i) input data to ensure it replicated (as accurately as possible) observations made during the opportunity mapping field reconnaissance surveys; and ii) delineating not only the sub-catchment tributary feeds but the sources, pathways and receptors, to better understand impacts in the final phase. Adhering to recommendation by Imbeaux (1982), the linked 1D/2D model using xpswmm © and Flood Modeller Pro © (both academically established, semi-distributed numerical models) was able to represent the time-area method, whereby runoff obtained can be related to a storm hydrograph and subsequently considered in relation to the time the hydrograph takes to reach the catchment outlet.

3.6.3 FEH input hydrographs

The FEH model for the generation of storm hydrographs is based upon a two parameter unit hydrograph: Standard Percentage Runoff (SPR) and time-to-peak (Tp). The Tp is defined as lag between rainfall centroid (inlet) and the peak of the flow hydrograph (outlet). The SPR is captured as the total rainfall percentage that leaves the catchment area as saturation excess (Kjeldsen 2007).

The 100-year (12 hour storm duration design event) generalised-unit-hydrograph (GUIH) and ensuing outflow hydrographs (using the FEH), are presented in Figure 3.25. The FEH GUIH provides a single peaked storm without a baseflow component, whereas the updated ReFH unit-hydrograph has an additional baseflow component, a lower peak and a longer receding limb. However, the ReFH was not used as the modelling packages contained depth-duration-frequency (DDF) information via parameters (C, D_1, E and F) in the FEH GUIH software user interface.

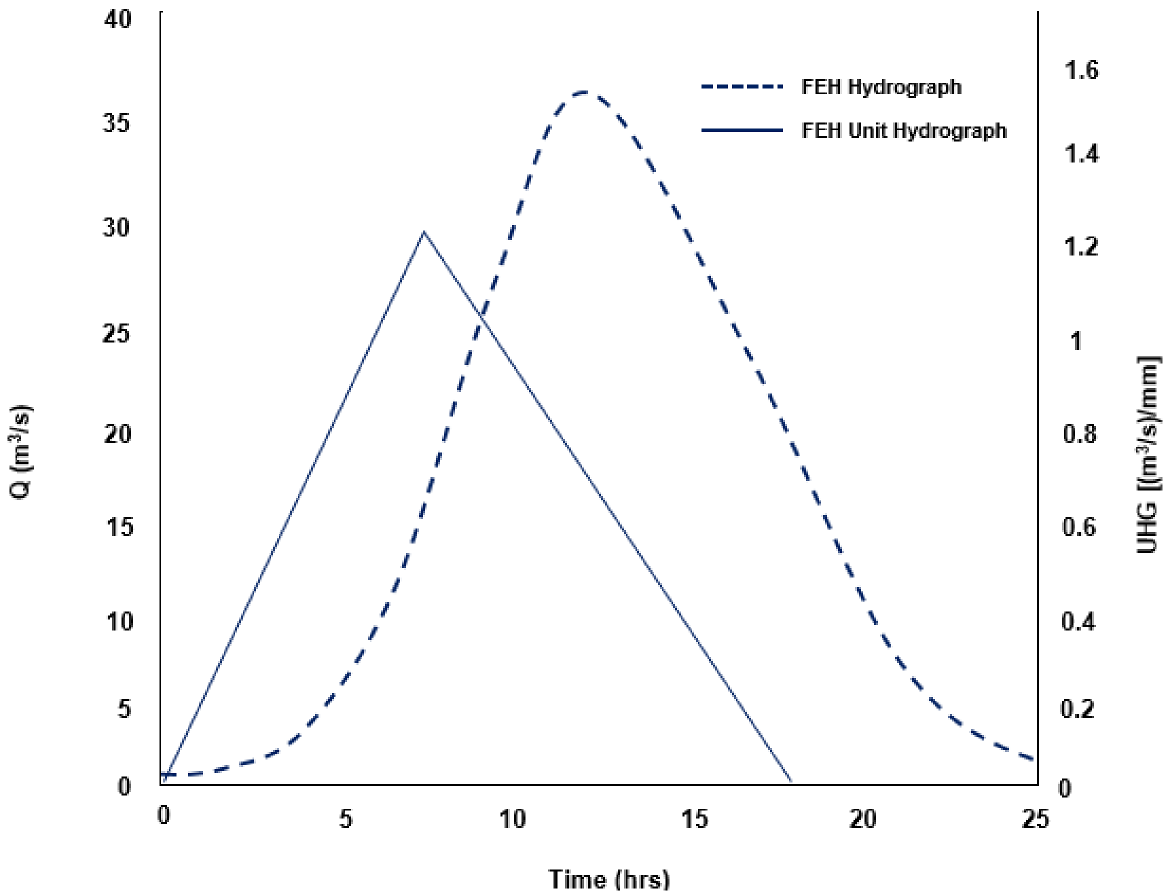


Figure 3.25 FEH for the 1%AEP, 12 hour design storm for all catchment headwaters inflows.

Using FEH rainfall-runoff inflows, design storm hydrographs were generated for the study site. A number events of different return intervals (1%AEP + Climate Change Allowance, 1%AEP, 3.3%AEP and QMED) for a 12 hours storm duration as per recommendations in Hankin *et al.* (2016a) to reflect rainfall intensity and total volumes in a realistic storm (outlined in Table 3.7). Such an investigation develops the understanding of the possible effects this type of rainfall event has on the Qp's

Table 3.7 Characteristics of FEH rainfall-runoff hydrographs used to form design events

Storm Duration		**Design Storms - Annual Exceedance Probability (AEP)**			
		1%AEP + 35%	1%AEP	3.3%AEP	QMED
12hr	Total rain (mm)	137.30	101.73	63.42	29.54
	Max intensity (mm/hr)	35.37	25.34	16.12	7.38

3.6.4 Catchment Hydrology: Observed Data

This section provides a summary of the observed data gathering through the long-term hydrological instrumentation used in the Stour Valley study site and an evaluation of the collected data. The flow characteristics of the River Stour at the downstream catchment extent (outlined in Figure 3.26) are analysed to gain an understanding of the history of high flows to assist with catchment characterisation and model calibration. The one active gauge station is used for Flood Forecasting Services (FFS), only recording high flows and peaks over thresholds and is situated on the River Stour (SP260405) at the Shipston Bridge (see Figure 3.23) and has been operational since 1972.

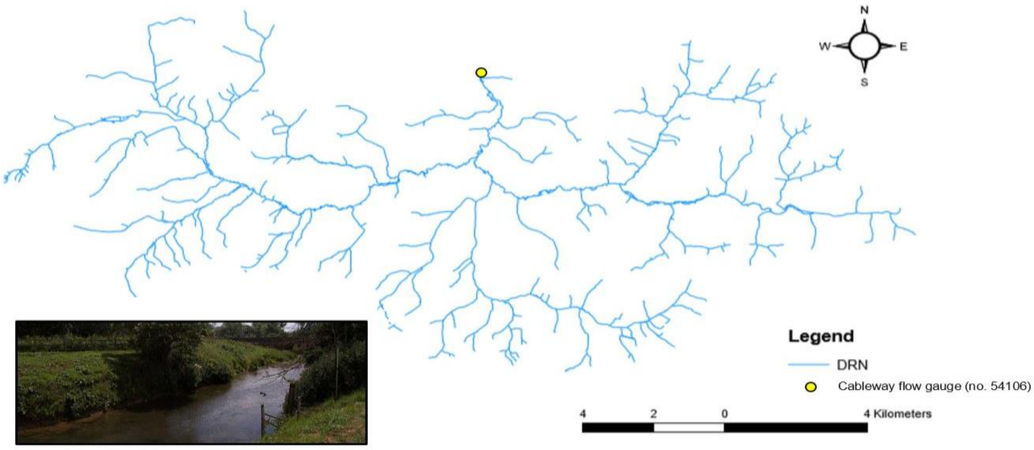


Figure 3.26 Stour valley catchment extent, including NRFA Station Gauge (no. 54106)

Figure 3.27 outlines the series of maximum instantaneous peak flows, also known as annual maximum (AMAX) data, within a water year (commensurate from October to September). Red bars indicate rejected annual maximum values. The Peak Over Thresholds (POTs) are triggered at 13.063 m^3/s, with limited high flows data for the top of the rating curve, in particular where the July 2007 event flooded the gauge and exceeded the upper limit of the rating curve. However, the AMAX data presented in Figure 3.24 indicates an increased linear trend within larger flood events from 1985 – 2018, with an increase in 24.24m^3/s, heavily influenced by the July 2007 175.33 m^3/s peak flow.

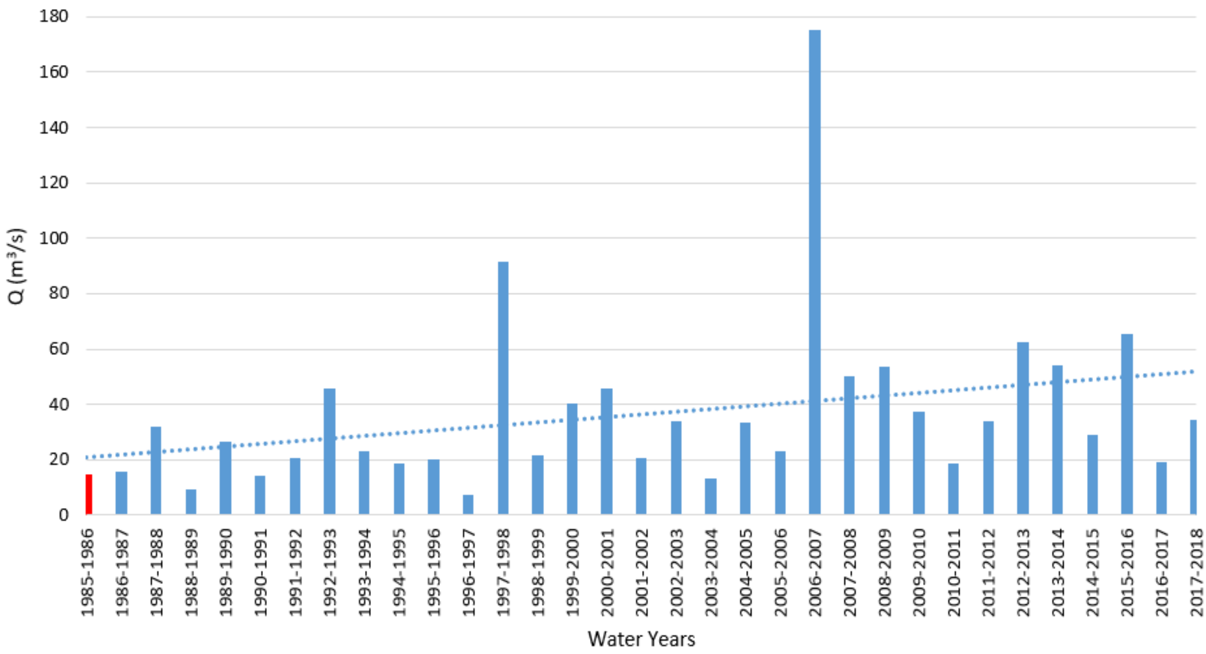


Figure 3.27 Recorded AMAX events 1985 – 2018 (Data sourced from NAFRA 2018).

The linear trend shown in Figure 3.27 was statically tested to POT data in Figure 3.28, which more representatively indicates all high flow events in any given year. There was a weak association between the water year and POT values, demonstrating the largest events (July 2007 and April 1998) as statistical outliers in the general fluvial response of the catchment between 1985 – 2018. It is important to note that this data series is still somewhat short-term in relation to wider climate induced 'flood rich and poor periods' (Dadson *et al.* 2017).

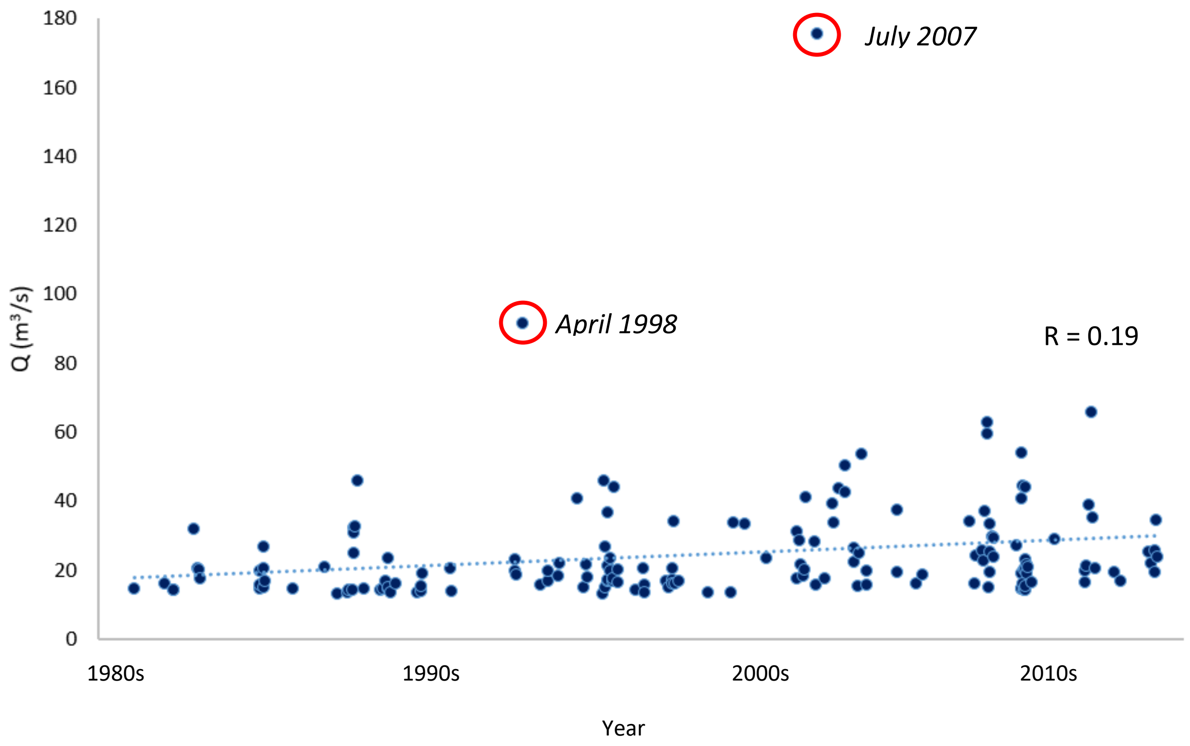


Figure 3.28 Recorded POT values 1985 – 2018 (Data sourced from NAFRA 2018)

The primary two flood sources that affect the Stour Valley catchment, include:

- Fluvial flooding: concerning the River Stour and its headwater tributaries across the Knee Brook, Nethercote Brook and River Stour (ordinary watercourse)
- Pluvial flooding: concerning surface water overland flows, exceeding artificial drains and water points of low-lying ground encouraging ponding on the surface.

Assessment of high flows (outlined in Figures 3.27 and Figure 3.28) and archival research of historic flood events (collated from Parish and Town Councils and Strategic Flood Risk Assessments) provided background to the flood history across the catchment and, in-particular, the key communities at risk outlined in Table 3.8. The flood events listed contain the events that caused internal flooding to properties and businesses across the Stour Valley, Warwickshire-Avon. Events that could not be identified in relation to particular communities due to no data were coded accordingly.

Table 3.8 Documented historic flood events across the Stour Valley's communities. ND = no data

Flood event	Chipping Campden	Blockley	Long Compton	Cherington	Stourton	Lower Brailes	Shipston-on-Stour
03.1947	X	ND	ND	ND	ND	ND	X
07.1968	X	ND	ND	ND	ND	ND	X
03.01.1985	X	X	X	ND	ND	ND	X
09.04.1998	X	X	X	X	X	X	X
24.12.1999	-	-	X	-	-	-	-
30.10.2000	-	-	X	-	-	-	-
20.07.2007	X	X	X	X	X	X	X
13.12.2008	-	X	X	-	-	-	-
24.12.2013	-	-	X	-	-	-	-
09.03.2016	-	-	X	-	-	-	-

3.6.5 Testing NFRM Performance Scenarios

This section outlines the parameters used in 1D/2D modelling packages xpswmm © and Flood Modeller Pro © to represent the co-designed NFRM opportunities. Much of the required data is imported from the first phase of catchment characterisation (objectives 1.1 to 1.3), and the digitised PGIS-NFRM scenario (objectives 2.1 to 2.4) developed in the second phase is imported and structures attributed accordingly, as outlined in Table 3.9. These parameters for NFRM techniques have been similarly applied and validated in large catchment models, including TOPMODEL (Odoni *et al.* 2014), CRUM (Pattison *et al.* 2016), JFLOW (JBA 2015) and Juke rainfall-runoff model (Owen 2016).

In order to understand the effectiveness of NFRM, a 'base-scenario' was tested against a 'PGIS-NFRM scenario' in order to fully understand the implications of NFRM on downstream flood risk for multiple flood risk scenarios. For the purpose of assessing fluvial flooding, the following indicators have been used to empirically test the performance of NFRM across the catchment scale:

- River height, represented in the form of the downstream peak at key receptors.
- River flow, represented in the form of discharge at key receptors.
- Peak timings, across multiple hydrographs to identify coupling and de-coupling of peaks.

The key attributes shared of the NFRM opportunities are that they are highly dispersed and small in hydrological scale when applied across the total catchment area. As a result of their hydrologically small scale and localised effects, NFRM is theoretically considered most effective in minimising flooding when applied in clusters across the catchment extent (as outlined in Section 2.5.1). Risk management authorities, including the Environment Agency, Lead Local Flood Authorities and Water Companies, represent headwaters as discrete homogenised areas and uniform inputs for flood risk analysis and wider water resource management (Beven 2009). This section will outline the integration of upstream models as a sequence of potential storage areas based on the PGIS co-designed NFRM opportunities. Due to the limit of the models active areas to the river and floodplain extents, features outside of the floodplain have been included in the representation.

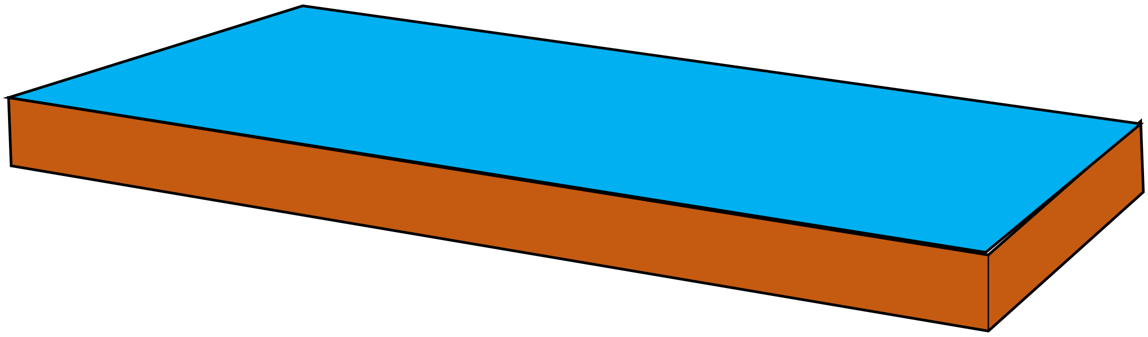
Table 3.9 Modelled representation of co-designed PGIS-NFRM Opportunities

NFRM Opportunity	Modelled representation
Woodlands (all, inc. hedgerows)**	Increased floodplain roughness – 0.15 *n* value
Online Storage	Online storage unit*
Offline Storage	Reservoir unit*
Leaky barriers	Increased channel roughness – 0.15 *n* value
Floodplain restoration	Reservoir unit*
River restoration	Alter DTM and channel network based on PGIS dimensions
Track drainage alteration**	Junction function in the 1D network to divert flows
Buffer strips	Increased floodplain roughness – 0.075 *n* value
Soil aeration**	Increased floodplain roughness – 0.050 *n* value
Winter crops**	Increased floodplain roughness – 0.050 *n* value
Conservation tillage**	Increased floodplain roughness – 0.050 *n* value
Swales**	Alter DTM for swale area based on PGIS dimensions
Ponds**	Alter DTM for pond area based on PGIS dimensions
Sediment traps**	Alter DTM for sediment trap based on PGIS dimensions
Bunds**	Alter DTM for bund area based on PGIS dimensions

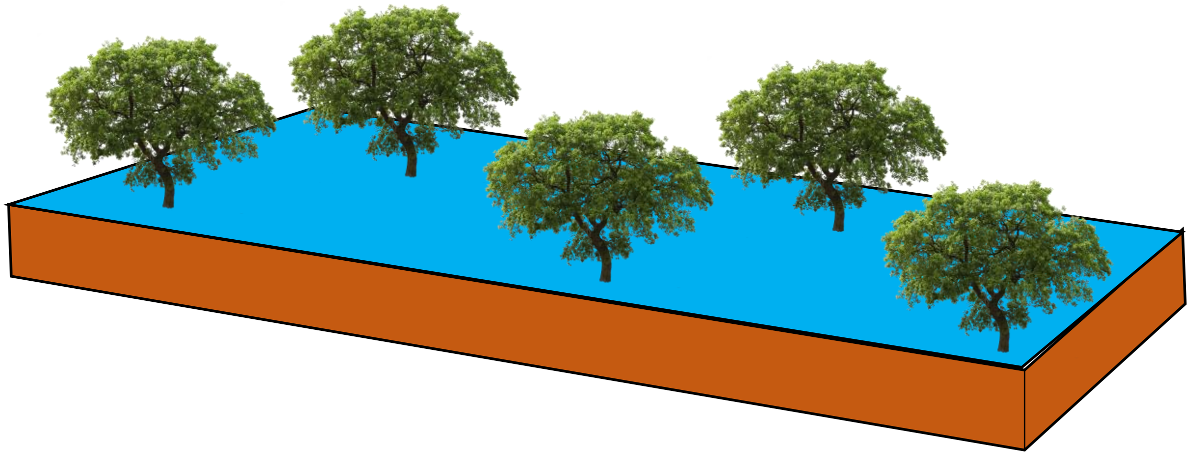
**Built-in features within the software, can be amended to represent area and volume*

***Note. Only opportunities within the active 2D area (floodplain) are represented within the model*

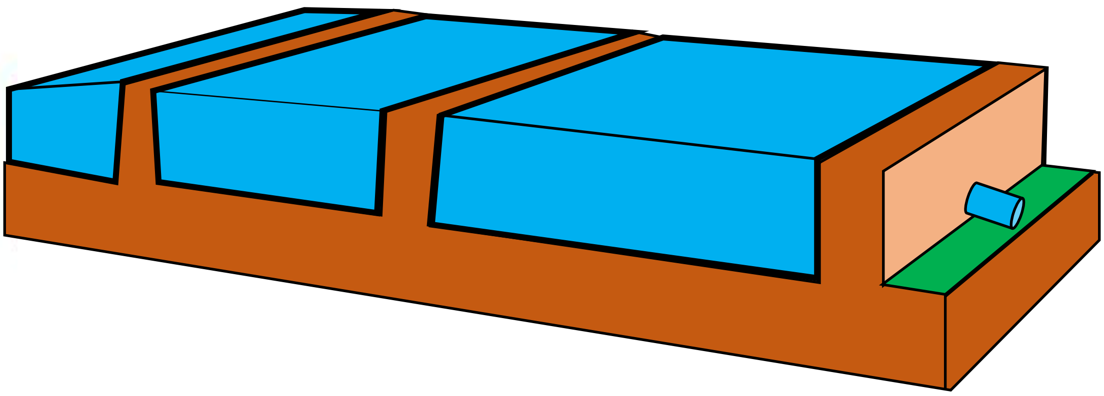
Wilkson *et al.* (2013) and (2015) highlight the importance of communicating NFRM opportunities effectively to decision-makers and stakeholders, especially when allowing for the high-level of uncertainty across heterogeneous changes to catchments in the form of NFRM techniques. Figure 3.29 outlines the representation of different NFRM opportunities in the 2D active area of the model domain across the assortment of opportunities (Hall and Solomatine 2008). This includes changing roughness and altering DTM to represent storage units within the floodplain.



- **Floodplain**: Buffer strips, soil aeration, winter crops and conservation tillage
    - No storage, shallow depth
    - Medium Manning's *n* value for surface roughness: 0.050 – 0.075



- **Floodplain**: Woodlands (all types) and hedgerows
    - No storage, medium depth
    - High Manning's *n* value for surface roughness: 0.15



- **Storage RAF features**: Offline storage, swales, ponds, sediment traps, bunds
    - High storage, high depth
    - Altered DTM values based on PGIS-NFRM opportunities

Figure 3.29 Schematic effects of NFRM opportunities on flood flows (adapted from Jacobs 2016 and Owen 2016)

The modelling utilises TUFLOW as a 2D hydrodynamic modelling package (developed by Lamb *et al*. 2009), benchmarked in previous similar modelling studies that used other 2D inundation (Ghimire 2013, Ghimire *et al.* 2014, Hunter *et al*. 2008). The modelling framework develops the blanket rainfall method (see Hankin *et al.* 2008 for example), which was developed in this study to accommodate the FEH rainfall—runoff losses model (Kjeldsen *et al.* 2005) (similarly used for the RoFSW model dataset used in the PGIS-NFRM exercise (Environment Agency 2017a)). The model incorporates spasmodic gross rainfall, using the FEH rainfall-runoff calculated losses model. Rural FEH losses are controlled by the maximum storage capacity of soil (C_{max}) - estimated using PROPWET and BFIHOST values from delineated FEH catchment descriptors. The floodplain areas has been characterised using a DTM (2m) with the use of LiDAR (79% coverage, mostly lowlands) and OS DTM tiles (see Table 3.1).

Varying coefficients for surface roughness were adopted based on LCM2015 land cover data, using the same RoFSW modelled roughness coefficients, provided below in Table 3.10. The Manning's n values are varied according to the Feature Codes of the LCM2015 dataset (CEH 2015) based principally upon Chow (1959), and hillslope hydrology reviews from Holden *et al.* (2008) and Medeiros *et al*. (2012). The values vary to take account of the hydraulic roughness of different land covers and their influence on broader, shallow-water flow patterns (Aronica *et al.* 1998, Myres *et al.* 2001, Birkinshaw *et al.* 2011, Gao *et al.* 2015, 16).

Table 3.10 Manning's hydraulic roughness values (based on Chow 1959, Gee et al. 2017)

Land Cover (LCM2015)	Manning's Hydraulic Roughness Coefficients
Woodland (all types)	0.150
Shrub	0.125
Arable	0.030
Urban (including roads and pavements)	0.020
Pasture (improved grassland)	0.035
Rough grassland	0.060

3.6.6 Model Calibration and Sensitivity Analysis using Observed Data

At hydrological small (<10km^2) gauged sites it is possible to calibrate and subsequently validate the parameters of a model against observed discharges; at ungauged larger catchments there is an estimation of the parameter values in order to make predictions known as sensitivity analysis (Beven and Binley 1992, Heathwaite *et al.* 2005). This section will outline the approach applied to the large, rural, poorly gauged catchment in order to calibrate the model and indicate the parameters' sensitivity to respond to rainfall. The analysis will assess annual totals before investigating event-based observations from the downstream extent gauge in Shipston-on-Stour, with further historic gauge details covered in section 3.6.4. The data covers a 43 year period from 1977, including 8 events that caused internal flooding to properties and businesses across the catchment, as presented in Table 3.8. Due to the size of the catchment (187km^2) it was unfeasible to install enough gauging stations to identify localised flood patterns and flood wave propagation over a long enough baseline period as part of a before-after, control-intervention (pre- and post-NFRM) monitoring network.

In recent years, availability of high resolution data regarding hydrological influences in the rural environment has enabled a much more informed understanding of how our catchments are affected by the two principle elements of flood generation, rainfall and runoff. However, whilst high resolution data availability has increased over the last few years, since the avocation in the Pitt Review's (2008) twenty-ninth recommendation, modelling has required an ability to recognise the uncertainty of the catchment representation and the parameters for such estimations (Environment Agency 2011 and Copper and Ming-Li 2017). Whilst considering NFRM, some level of quantification needs to be undertaken to determine both the baseline (i.e. the current "as is" level of risk) and the level of risk reduced once the intervention is in place. Allocation of funding on a national basis is governed by such analysis and is often reliant upon the use of detailed modelling to provide an evidence base sufficient to be used for decision making (Woodward, Kapelan and Gouldby 2013). Quantifying the impact of NFRM is a far more complex undertaking and results are often provided with wide-ranging confidence bands to acknowledge the level of uncertainty in applied methods (Rose *et al.* 2013).

The model parameters applied in this research have been calculated from i) catchment descriptors, ii) varied Manning's 'n' values for surface roughness applied to land cover and, iii) the precise location defined by landowners and farmers in the PGIS NFRM Opportunity Mapping part of the research. The latter is essential in ensuring models accurately represent the co-designed NFRM scenarios. Due to the catchment size and computational run times, tributaries were delineated, coded, and linked with a routing model. This provided an understanding of relative sub-catchment Tp as well as propagation of 'flood waves' (inlet FEH hydrographs) through the network to large hydrological scales. Such a hydrological up-scaling process provided complex modelling challenges, extensively discussed by Pattison *et al.* (2017), Quinn *et al.* (2017), Metcalfe (2017) and Lamb *et al.* (2015). The nested models applied input FEH hydrographs into the source (high order streams), and subsequently simulated the effects to enable the output of the above sub-catchment to input the next delineated downstream channel until reaching the Stour_out gauge in Shipston-on-Stour, the pour point of the whole catchment area. Mass balance model checks were also undertaken to ensure there were no structural inaccuracies with the model with flow being lost or gained in the network and displayed in Figure 3.30.

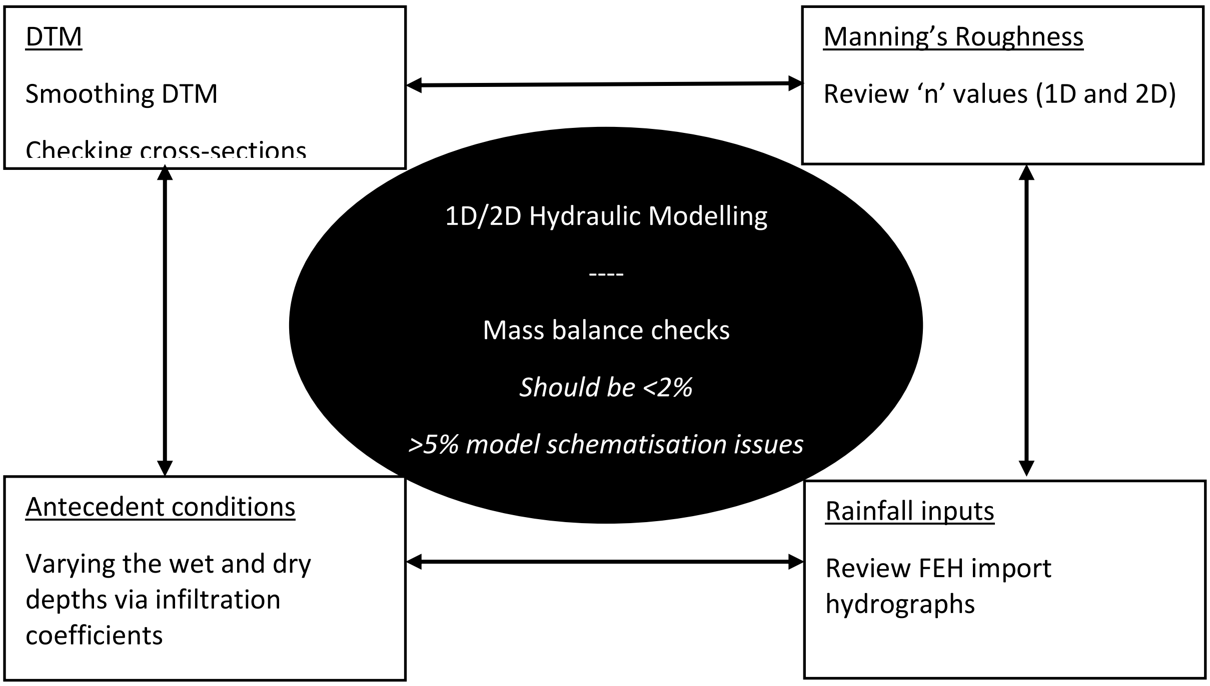


Figure 3.30 Mass balance checks to identify losses and gains in the model

Preliminary mass balance checks of the constructed baseline model revealed significant incongruities in the FEH storm hydrograph mass losses in the model. The FEH storm hydrograph volumes at the inflows typically exceeded the total mass leaving modelled domains outlet nodes between 2% - 3.7%. To calculate this with the limited available observed rainfall and upstream flow data, an approximation was conducted using a sinusoidal function (developed by Calder 1986) and a 'reverse engineering approach' of inflow and outflow hydrographs (Crook *et al.* 2009).

Two probable influential factors where identified to explain the mass imbalance:

1. Whilst mass imbalance was <5%, schematic issues with in-channel representation of structures (such as weirs) were amended to regain mass in the downstream hydrograph, amending spill rates and channel cross-sections.

2. DTM smoothing of the floodplain was undertaken in order to enable dynamic flow between the channel and the floodplain, it was identified that certain areas of floodplain were retaining water and therefore leading to mass loss in the downstream hydrograph.

In most other modelled studies, standard modelling techniques have been applied to test scenarios related to increased drag as a result of floodplain planting or the attenuation effect of leaky barriers and runoff attenuation features (RAFs). This novel method utilised 1D-2D linked hydraulic models capable of representing complex in-channel conveyance mechanisms (1D) and floodplain flows across detailed elevation grids (2D), however, with this complexity comes an increase potential for error. Therefore, this section also presents the model calibration to observed downstream flow data in order to compare the simulated with observed flow data of a similar sized event to that simulated. Flood frequency analysis of the March 2016 event was considered a 1%AEP event in the Shipston area (Environment Agency 2018d), which was therefore tested to the 1%AEP FEH design event.

Using the March 2016 event outlined in Figure 3.31 (1%AEP, 12hr storm duration), the magnitude of Qp was predicted with an error of -0.91% (-0.294m) within the model. In relation to discharge, based on the rating curve (converting stage to discharge) peak errors were -54.44 m^3s-1 (-12.45%). In relation to the timing of flood peak, Tp, the prediction was more accurate with an error +0.12 hours (+0.36%). Therefore, the Nash-Sutcliffe coefficient for the March 2016 (1%AEP) model is 0.84 and the root mean square error (RMSE) is ±0.026, which according to recommendations by Croke (2009), are within acceptable values in hydrological and hydraulic flood models, >0.65.

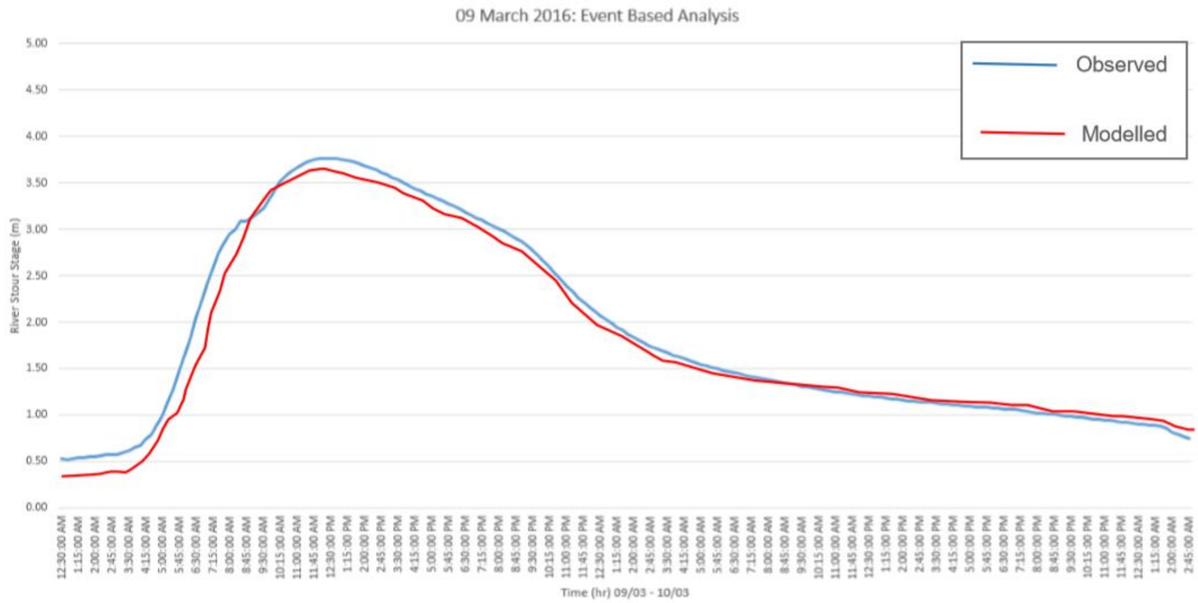


Figure 3.31 Model calibrations for Stour_out model assessment for March 2016 event

Model calibration by altering the Manning's 'n' value for surface and channel roughness (values provided in Chow 1959) has recognised significant variability in outputs. It has been identified that the model's flows were very sensitive to changes in these values, controlling the resistance of in channel and overland flows in relation to downstream river flows, by increasing Manning's and thus reducing network conveyance (Lane 2005). It was identified that localised Manning's changes in stream value and bank crest profile could significantly alter the hydrograph response to the FEH input storm. Capita Symonds (2008) identified a number of fences along the bank crest, increasing Manning's in comparison to natural stream roughness values by 0.035, from a channel with stones and weeds (0.035) to a lined channel with heavy bank growth (0.070).

Increasing the peak stage at *Stour_out* to more accurately represent the observed data was attempted by increasing the Manning's in upstream communities that could also have the same conveyance-reducing effects on high flows as identified in Shipston-on-Stour. However, when roughness was raised by 0.035 in the upstream channels through Chipping Campden, Blockley, Lower Brailes, Cherington and Long Compton, the modelled hydrograph varied significantly to the observed March 2016 event. Figure 3.32 outlines the hydrograph response in Shipston-on-Stour as a result of these raised Manning's 'n' values in the streams above the Stour scenarios. In the raised roughness value at Cherington, the Qp was more accurate to the observed event, but the Nash-Sutcliffe coefficient lower and RMSE higher than the roughness increase only in the reach at Shipston-on-Stour simulation. Table 3.11 outlines the Nash-Sutcliffe comparisons of different scenarios' accuracy to the observed event.

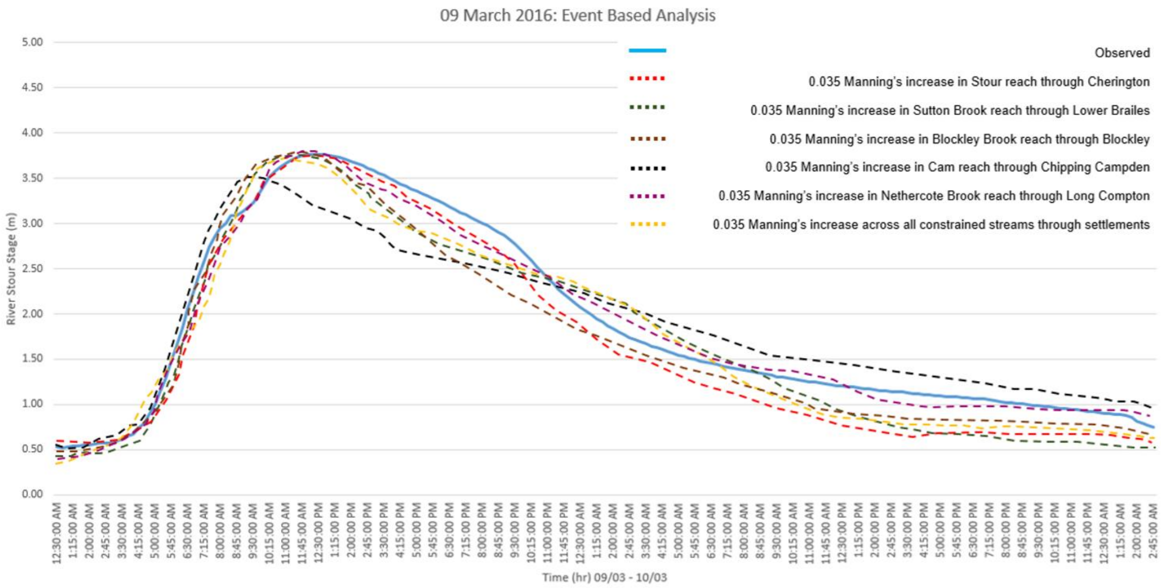


Figure 3.32 Sensitivity analysis of different channel roughness scenarios

Table 3.11 Sensitivity analysis of models. Nash-Sutcliffe and RMSE value of modelled scenarios

Scenarios	Cherington	Brailes	Blockley	Campden	L Compton	All	Shipston
Nash-Sutcliffe	0.72	0.78	0.69	0.54	0.70	0.65	0.84
RMSE (±)	0.041	0.039	0.089	0.108	0.068	0.092	0.026

3.7 Chapter summary

This chapter outlined the data sources, processing and methods undertaken in accordance with meeting the research aims and objectives. In regards to the first aim, this entails the sourcing, mining, processing and publishing of geospatial physical, hydrological and social data to publish FIPs. The participatory methods required to meet the second aim using PGIS to co-design NFRM opportunities were detailed, in order to test the performance of a 'realistic' NFRM scenario across the Stour Valley.

3.7.1 Catchment and data

The Stour Valley catchment in Warwickshire, UK, have been analysed through desk-based physical, hydrological and social data to develop a distributed understanding of the generation and propagation of floods across the 187km^2 catchment. Publication of the GIS data into FIPs (outlined in sections 3.3 – 3.4) provides an overview of the topography, soil, geology and land cover to establish an understanding of the hydrological regime and potential flood hazards to assist the co-design process.

3.7.2 Co-designing NFRM opportunities

Section 3.5 detailed the methods used to work with farmers and landowners to co-design NFRM opportunities across the meso-scale 187km^2 of the Stour Valley. Figure 3.21 provides the detailed framework used to co-design NFRM with participants, mapping local knowledge and incorporating this information into the complex decision-making process associated with NFRM. This method is tested in a Pilot Farm study site in the next chapter, identifying the robustness and replicability of the co-design process, along with lessons learnt when upscaling this process.

3.7.3 NFRM performance modelling

Section 3.6 detailed the model type and build for investigating NFRM impacts on catchment flood risk across multiple return periods. The lumped FEH rainfall-runoff model makes good use of available GIS and hydrometric data for parameterisation for flow generation and propagation. This provides a basis for assessing management impacts despite the uncertainties regarding the parameterisation, limited observed hydrology and in the data being modelled.

4 Pilot Farm Evaluation

4.1 Introduction

This chapter covers the results of the pilot farm study where PGIS was first trialled to co-design NFRM opportunities and test the robustness of the methodology in order to meet the second aim. Section 4.2.4 outlines the raw PGIS data gathered during the mapping exercise, including the local flood knowledge drawn onto a clipped basemap. It then evaluates the replicability of the pilot engagement methods (objective 2a) to identify sources and pathways of flood flows (objective 2b, section 4.2.5) and NFRM opportunities (objective 2c, section 4.2.5). Section 4.2.6 explains the building of a framework to evaluate NFRM opportunities in relation to different influential factors at the wider catchment scale (objective 2d, section 4.2.6).

4.2 Pilot Farm Investigation

The pilot farm study investigated the methods for NFRM opportunity screening, informed by local participant knowledge and applying a risk based approach, using the example of a livestock farm outlined in Figure 4.1. Key characteristics of the pilot farm are summarised in Table 4.1, and this desk-based site characterisation provided to the participant within the Farm Information Pack (FIP) is included step by step in Sections 4.2.1 – 4.2.3, in order to illustrate the engagement and knowledge sharing process. Previous instances of flooding and overland flows had caused disruption to the farm business, and NFRM was considered a sustainable alternative to traditional agricultural drainage practices. The principles of NFRM by slowing, storing, disconnecting and (if possible) infiltrating flood flows were supplied to the participating farmer in the form of a *Practical Guide* (Appendix C), enabling the participant to engage from an informed position around NFRM techniques. The document also contained links to additional guidance to support any further reading (SEPA 2016, Somerset FWAG 2016, Stroud District Council 2016, CREW 2017b, Yorkshire Dales 2017, Environment Agency 2017c, Freshwater Habitat Trust 2017). Stages in the pilot investigation are summarised in Figure 4.2– Figure 4.4, and the main findings are recorded in Table 4.2, using the same headings.

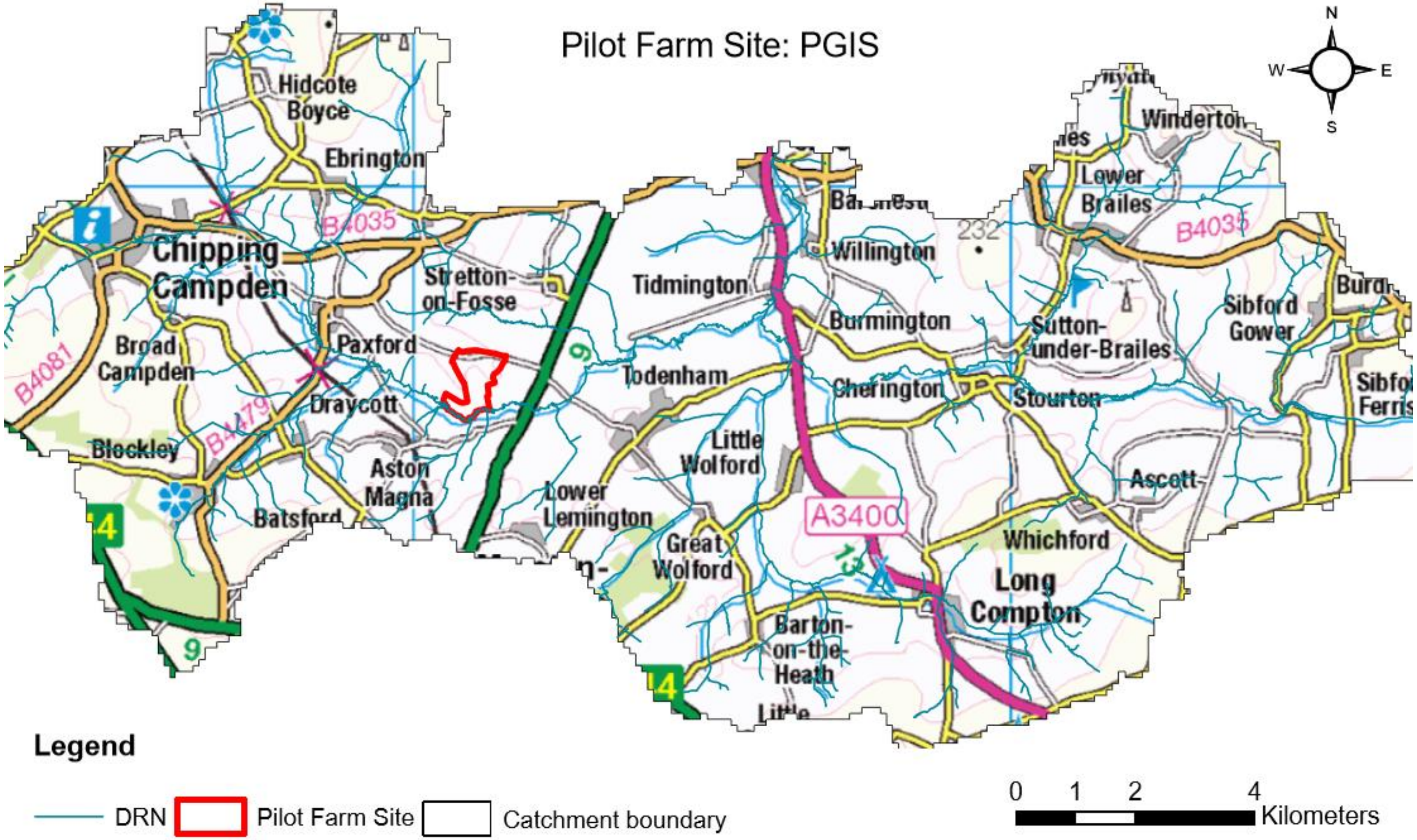
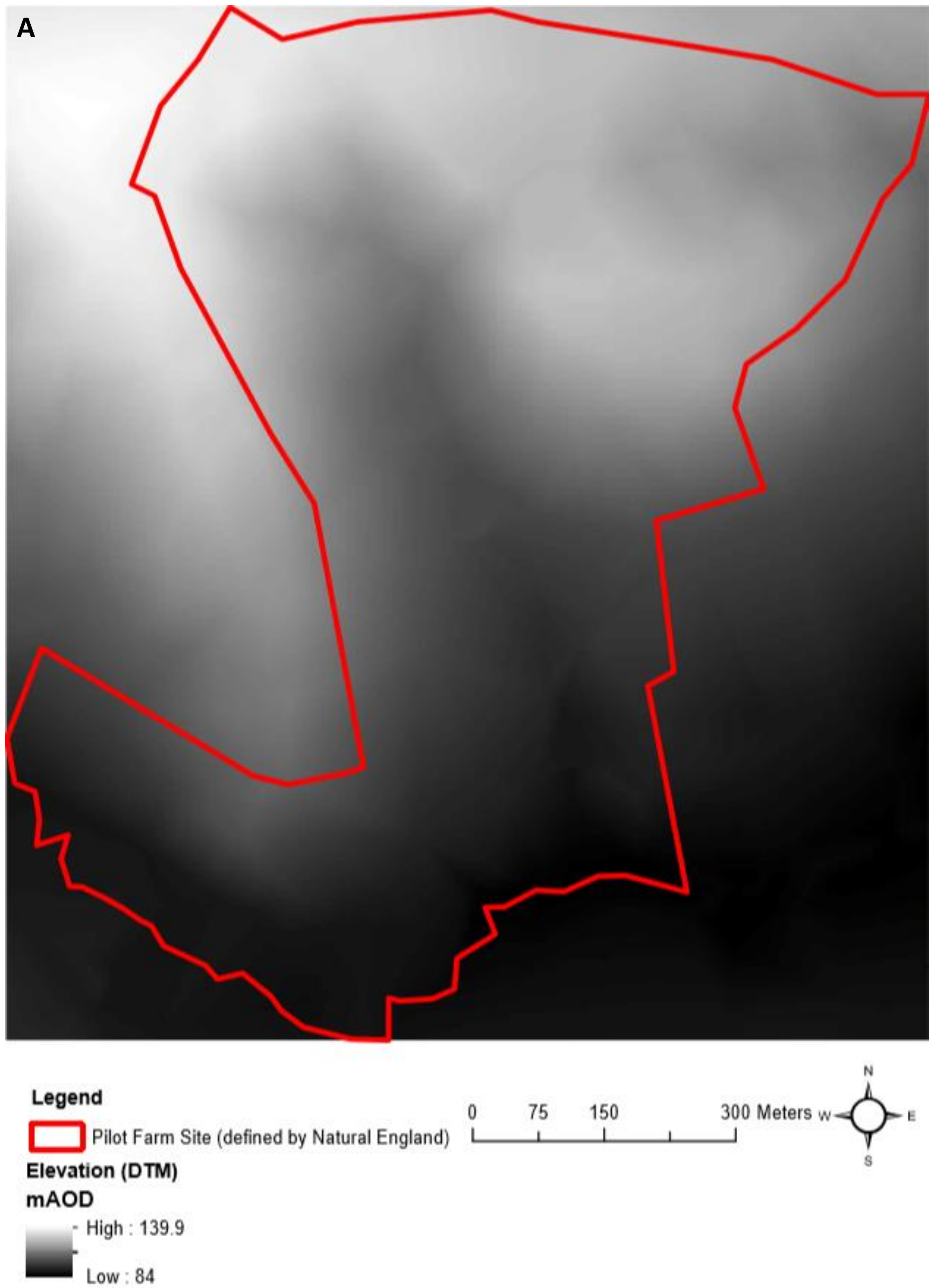


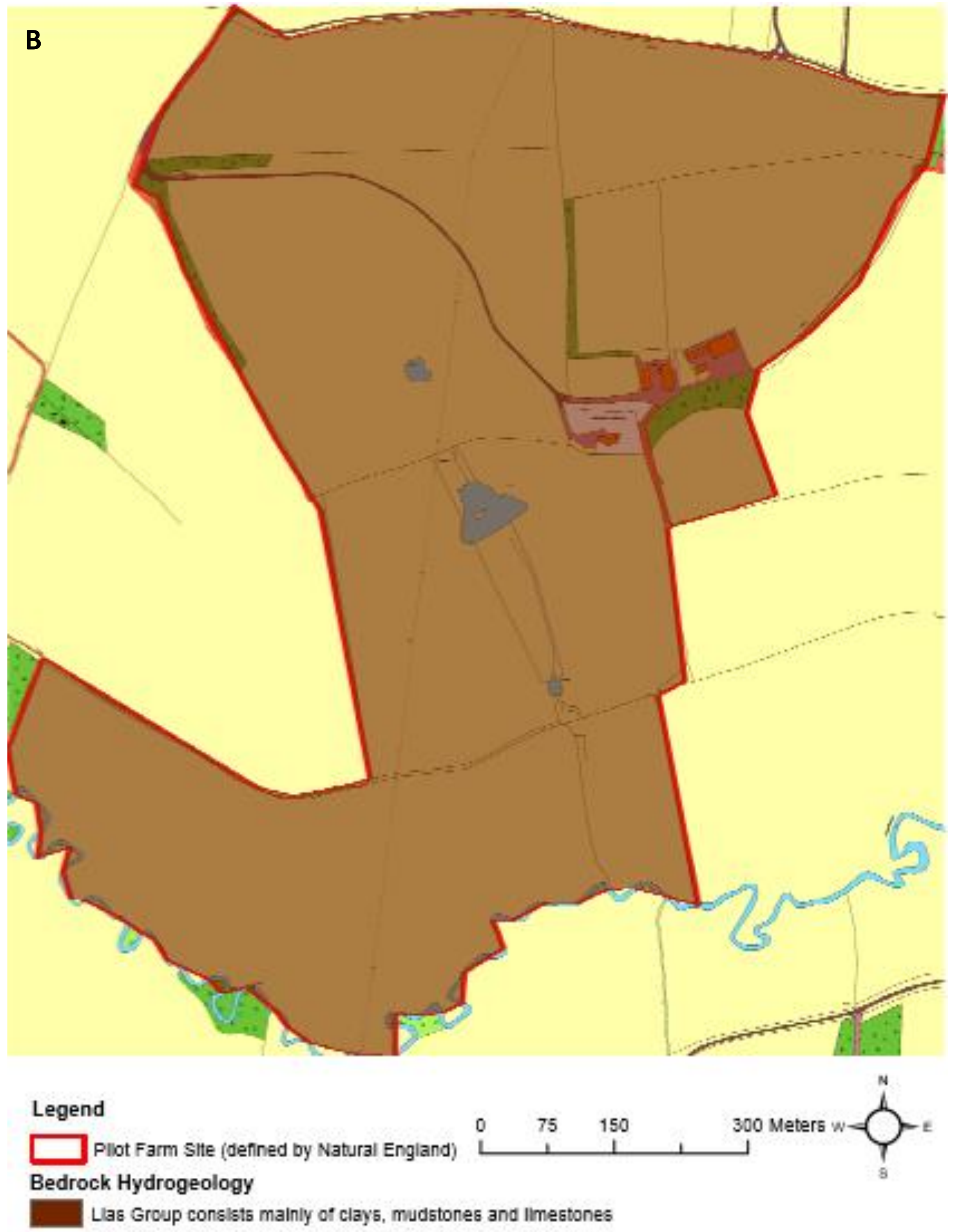
Figure 4.1 Location of PGIS pilot farm site, outlined in red. The farm equates to 0.31% of the total catchment area and 2.82% of the total 'useable' catchment, defined as those areas outside any constraints that could be potential farms/estate for NFRM.

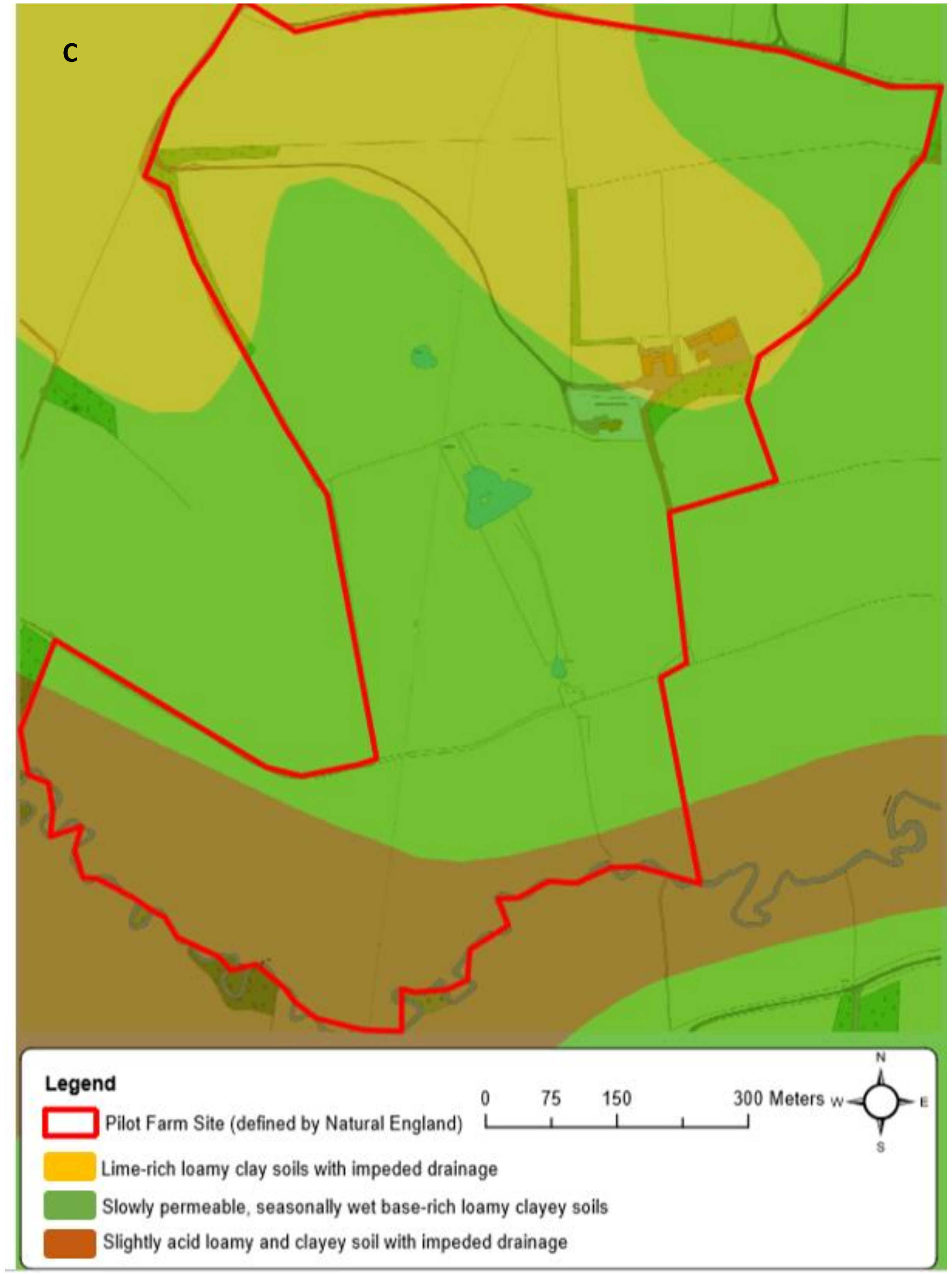
Table 4.1 Key characteristics of the pilot farm site determined from desk-based characterisation

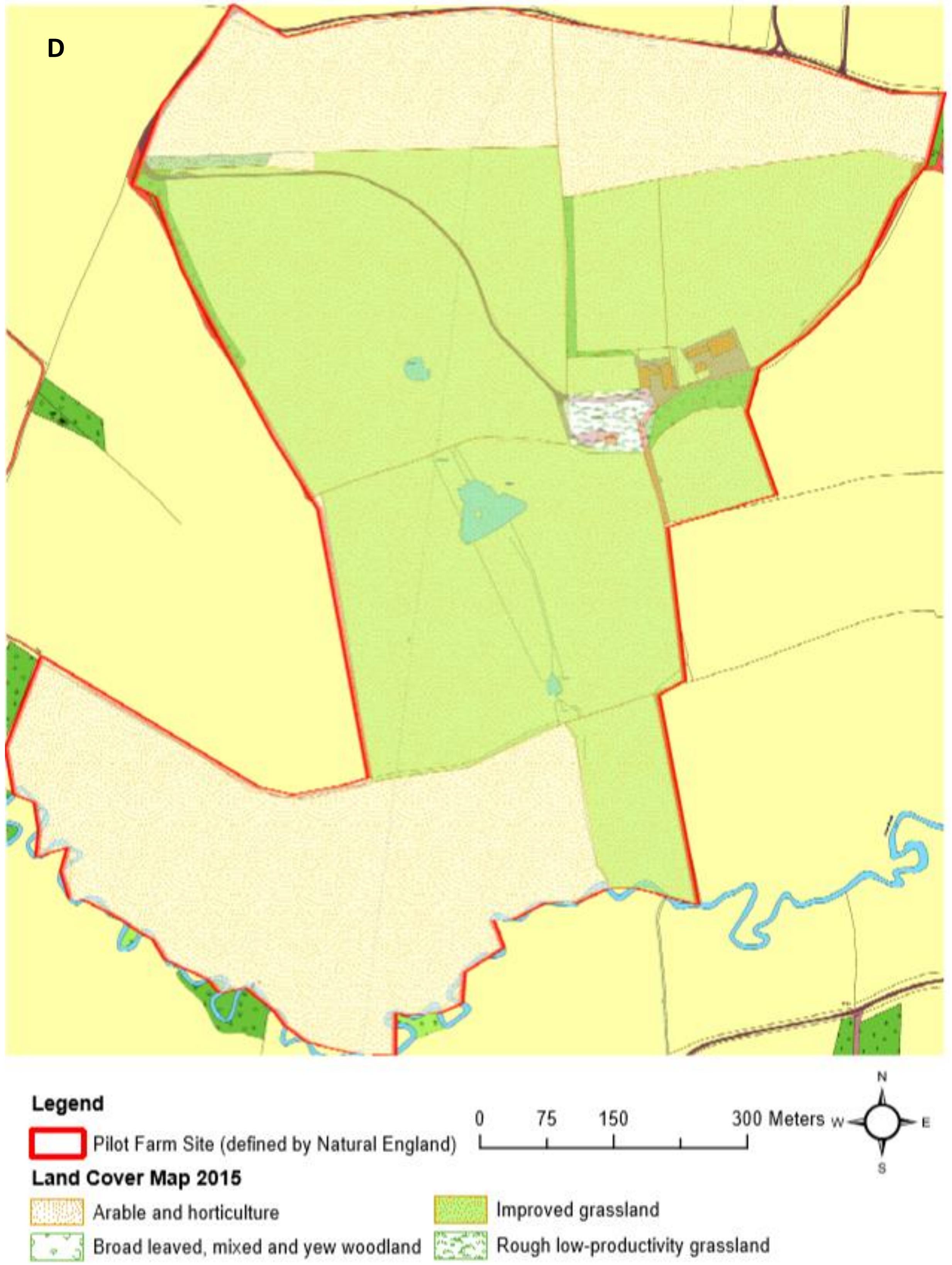
Slope	Geology	Pedology	Land Cover	Historic Land Cover	Flood risk	WFD	Sensitivities/constraints
				Figure references			
4.2 a	**4.2 b**	**4.2 c**	**4.2 d**	**4.2 e**	**4.3 a – c**	**4.3 d**	**4.4 a – b**
			Descriptions of desk-based catchment characterisation data provided to farmer in relation to individual holding				
A steep valley with ridge and furrow in the floodplain. Over a 148m slope to the channel the farms highest elevation is 124.06mAOD and lowest is 81.94mAOD, equating to a 132.12m elevation change across the farm.	. Largely Lias group with essentially no groundwater contributions. The mudstone sequence contains some limestone and marlstone rock forming local aquifers yielding small supplies. Limited capacity for infiltration.	High SPRHOST runoff from gleying clays (HOST class 25). Seasonally saturated and slowly permeable soils over impermeable clay substrates with no storage capacity.	Predominately improved grassland (75%) and arable use (22.9%), both of which provide limited hydraulic roughness and minimal resistance to flow pathways. Remaining 2.1% of land cover accounts for rough grassland.	Based on 1906 - 1936 land cover, there was a much denser network of hedgerows in the floodplain. However, the absence of two ponds within the valley indicates the features were installed after this date. The channel network meanders are just as extensive as they are compared to current land cover and detailed river network (2015), no channel modifications have taken place between 1906 and present.	A high degree of hydrological connectivity via the valley into the receiving watercourse. RoFSW 0.3%AEP, 1%AEP and 0.1%AEP conveyed into receiving watercourse, exceeding capacity of existing ponds. RoFR&S extents indicates extensive out-of-bank flows, especially to high probability, more frequent event. This indicates this floodplain is frequently inundated and has potential to provide additional upstream storage and/or hydraulic roughness.	The receiving watercourse is classified as having 'poor' ecological status. Based on analysis to a 14.6km^2 sub-catchment, 63% of the issues are attributed from diffuse agricultural pollution. 36% attributed from point source pollution.	Good to moderate (Grade 3) agricultural land classification, and therefore consideration needed on cost to farmer setting aside land for NFRM. Cotswold River Landscape Strategy identified area as an area for sensitive management of water voles. The study farm is under mid-tier Countryside Stewardship and requires careful consideration of potential NFRM that will not generate Permanent Ineligible Features (PIFs). The area does not fall within a SSSI, AONB or source-protection area.

4.2.1 Pilot Farm Site: Physical Characterisation






C
Legend
Pilot Farm Site (defined by Natural England)
Lime-rich loamy clay soils with impeded drainage
Slowly permeable, seasonally wet base-rich loamy clayey soils
Slightly acid loamy and clayey soil with impeded drainage
0 75 150 300 Meters
N
W
E
S


D
Legend
Pilot Farm Site (defined by Natural England)
Land Cover Map 2015
Arable and horticulture
Broad leaved, mixed and yew woodland
Improved grassland
Rough low-productivity grassland
0 75 150 300 Meters
N
W
E
S

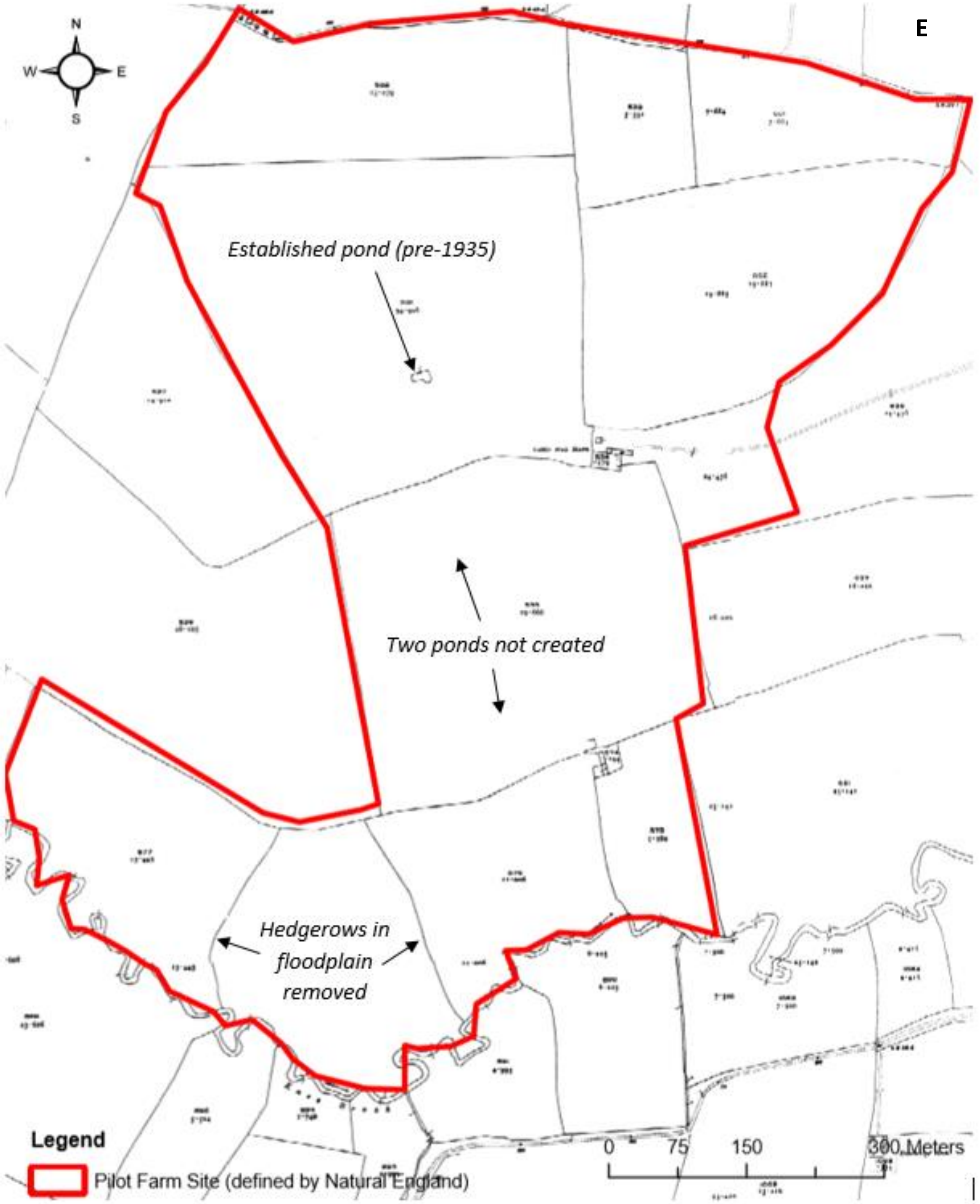
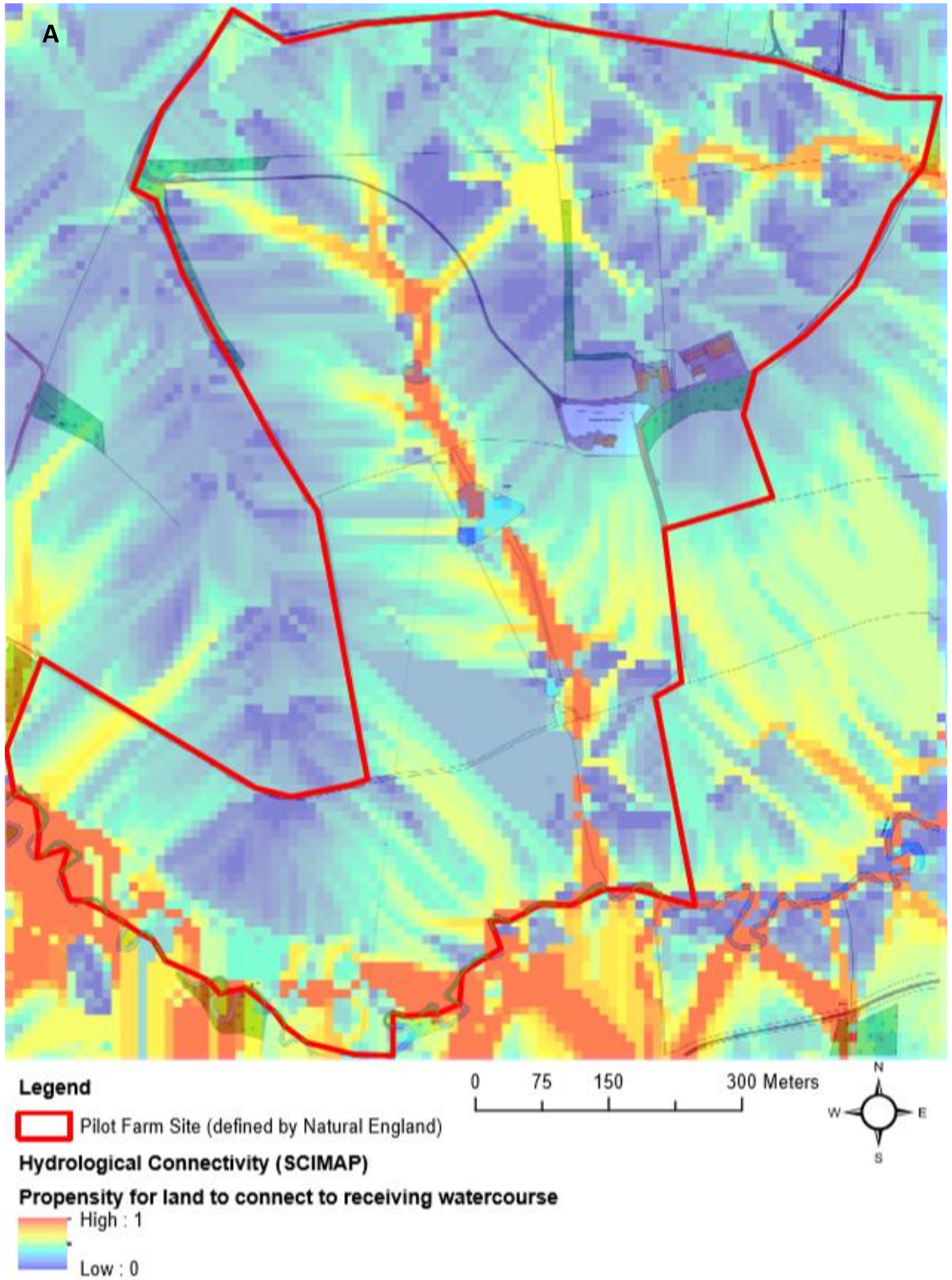
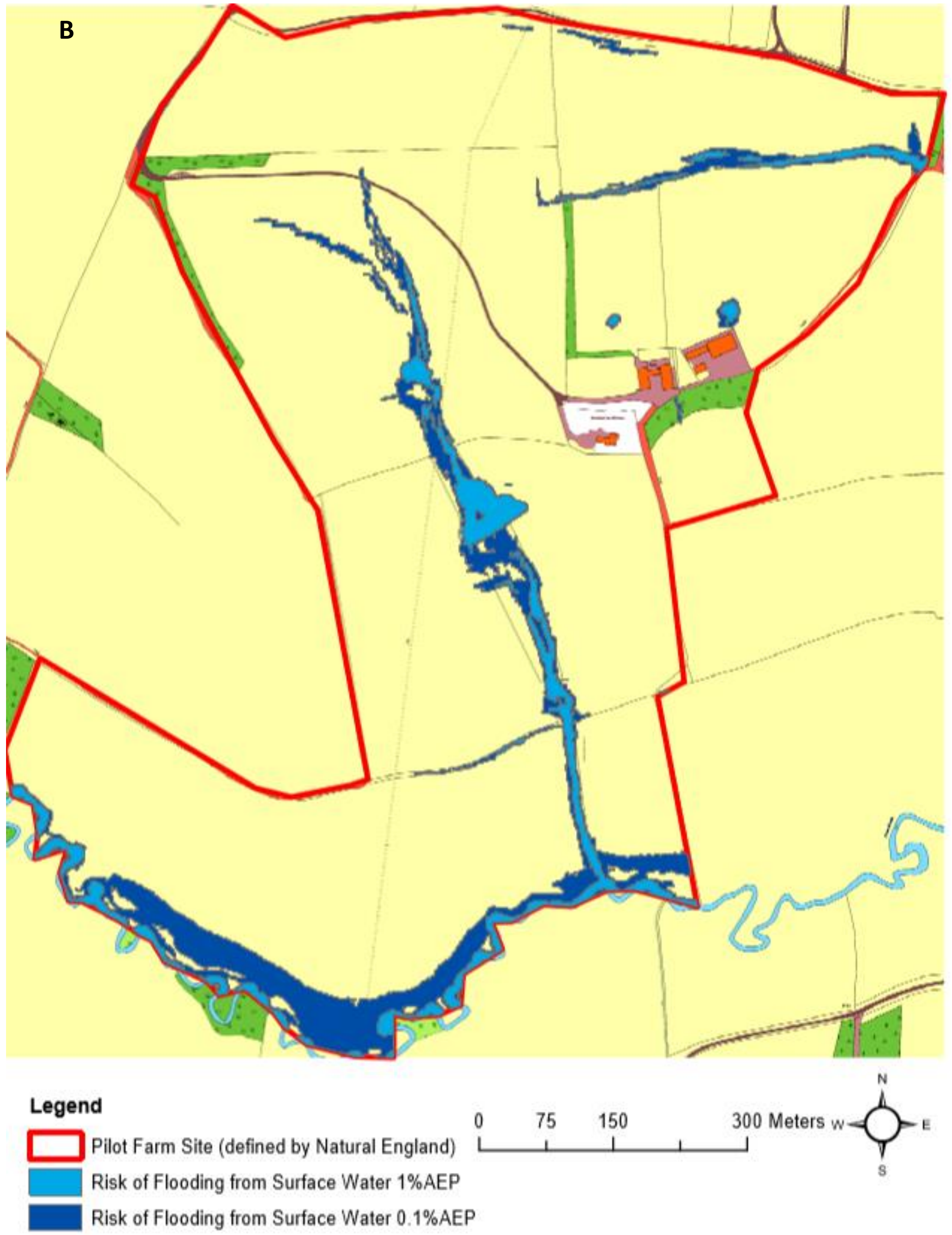


Figure 4.2 A) DEM of farm (LIDAR) (Environment Agency 2017e), B) Hydrogeology (BGS 2017), C) Pedology (CEH 2017), D) Present Land Cover (CEH 2017) E) Historic Land Cover (Dudley Stamp 1906 – 1936)

4.2.2 Pilot Farm Site: Hydrological Characterisation





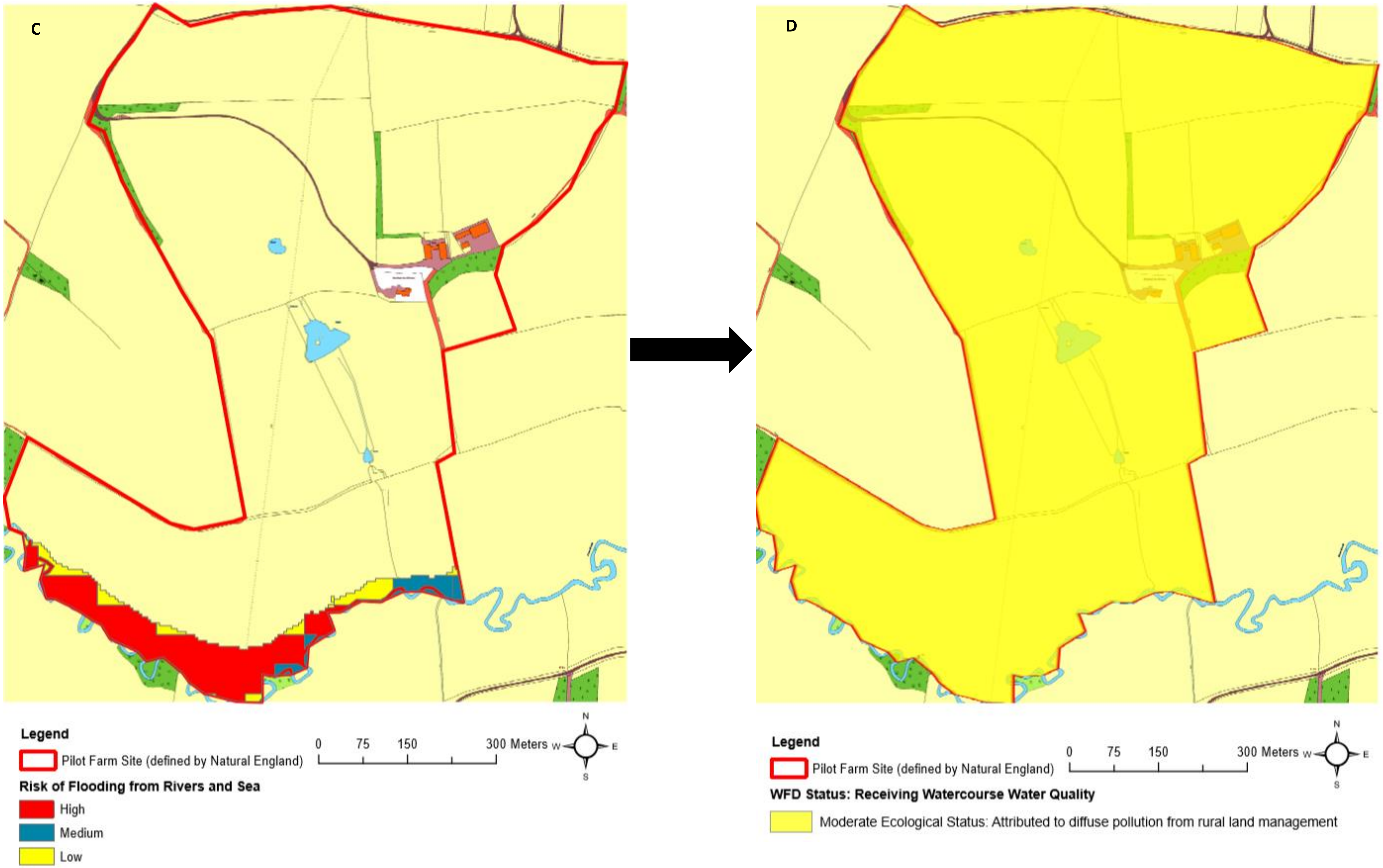


Figure 4.3 A) Hydrological Connectivity (SCIMAP 2017). B) RoFSW 3.3%AEP, 1%AEP and 0.1%AEP (Environment Agency 2017a). C) RoFR&S, low – high probability (Environment Agency 2017b). D) WFD status of receiving watercourse

4.2.3 Pilot Farm Site: Social Characterisation

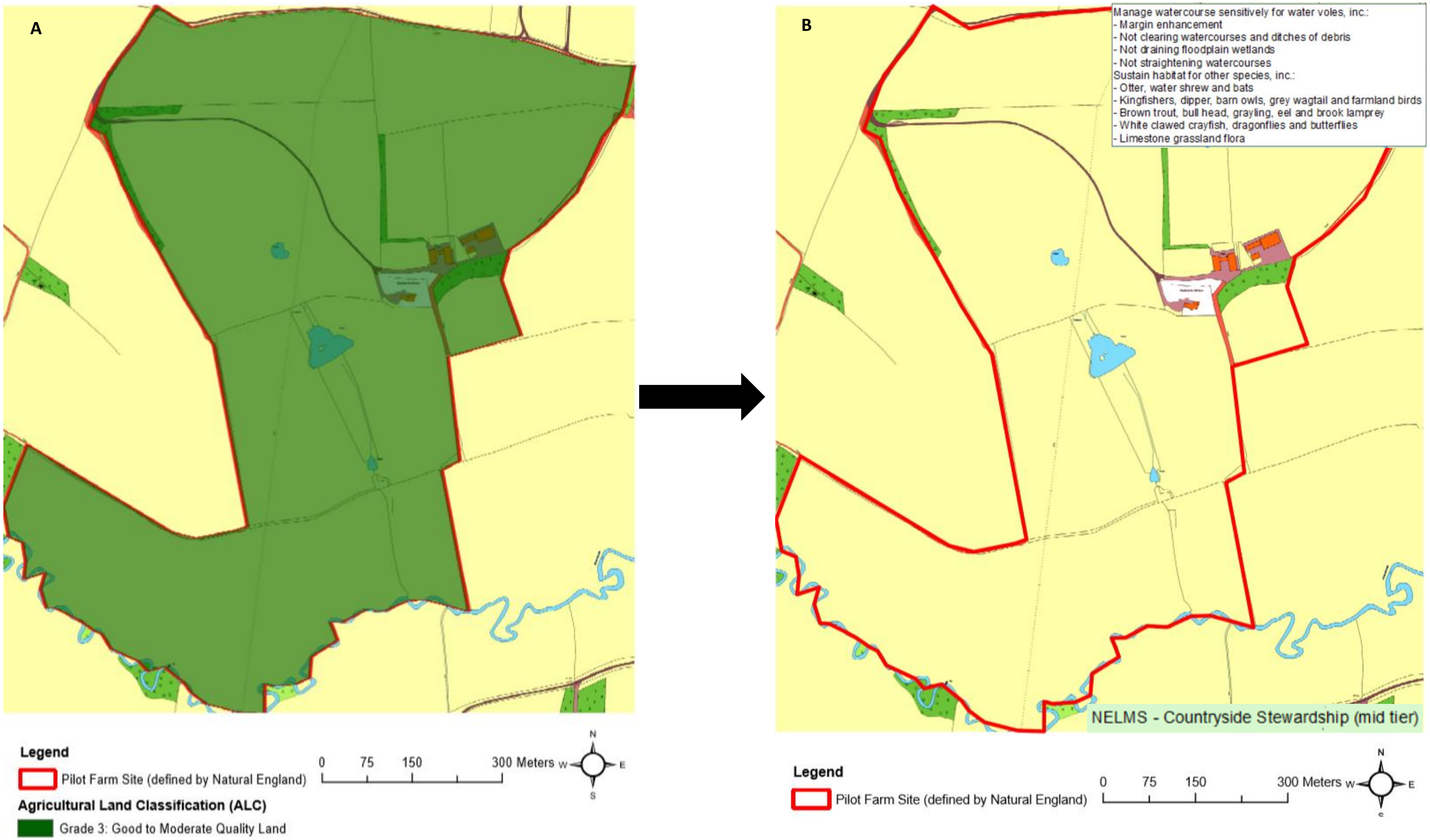


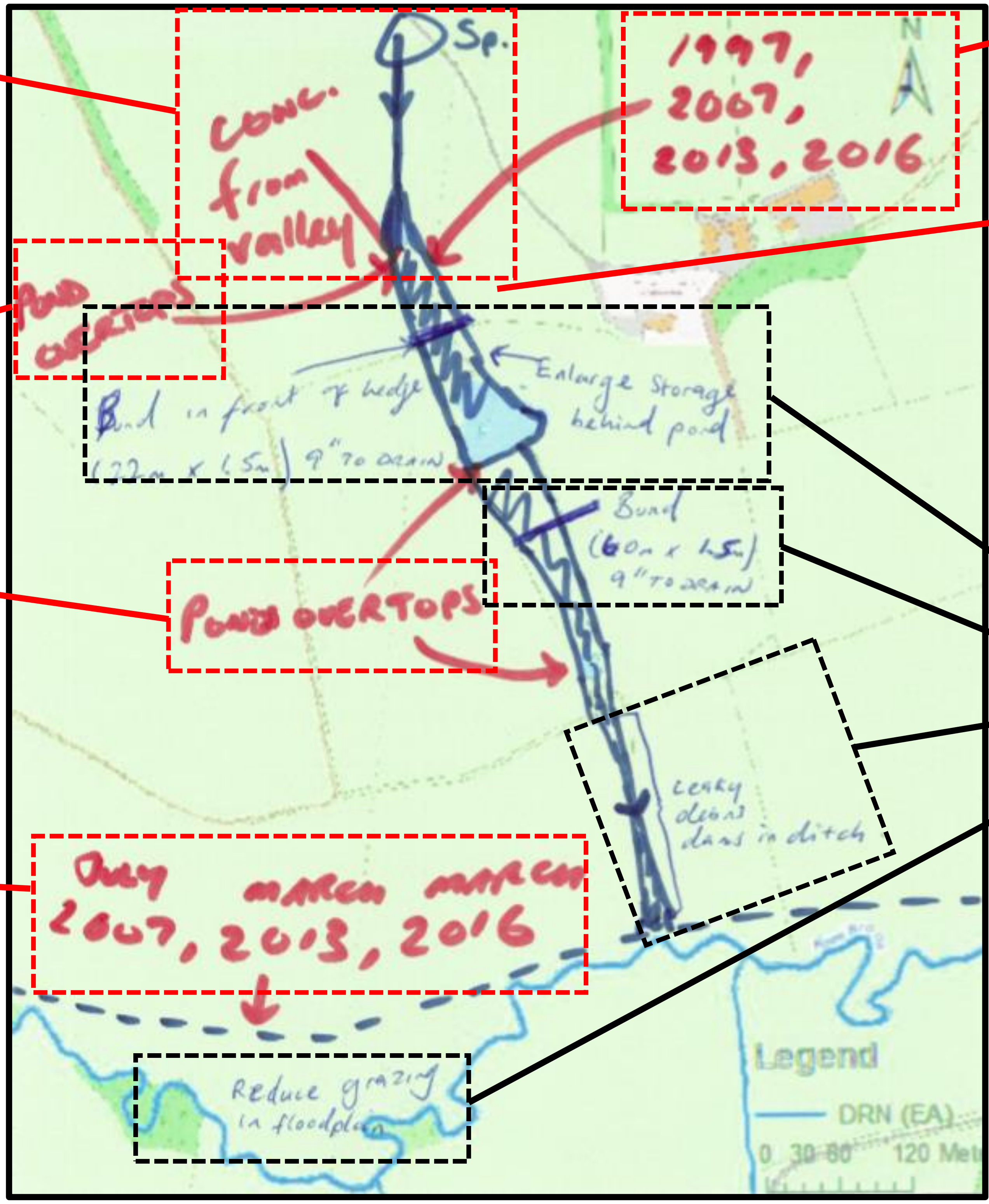
Figure 4.4 A) Agricultural Land Classification (Natural England 2016). B) Cotswold River Living Landscapes (Gloucestershire Wildlife Trust 2016) and existing and targeted environmental stewardship (Natural England 2017).

4.2.4 Pilot Farm Site: Raw PGIS Data

***Sources and pathways**: gravel spring identified, concentrated flow pathway outlined as the steep valley feeding the receiving watercourse*

***Sources and pathways**: Existing ponds identified as a water features that overtop in flood events (all reference events). This shows there is a lack of headroom capacity and potential for additional surface water attenuation.*

***Flood memories**: Events when out of bank flows occurred. Floodplain depth was noted to be anywhere between 2ft (0.6m) for smaller events (e.g. March 2016) and 3 ft (0.9m) for larger events (e.g. July 2007).*



***Flood memories**: Events when overland flow occurred*

***Sources and pathways**: Overland flood route and extents identified (in relation to reference events). Note the overtopping of all existing water features and the concentration of flood flows down the valley to the receiving watercourse. This was noted to be at a depth of approximately 2ft (0.6m), and only last for a maximum of 24 hours before the flow route became inactive after the event.*

***NFRM Opportunities**:*

- *Bund: 9inch (22.86cm) pipe to drain, above pond*
- *Enlarged pond area, increasing storage behind pond*
- *Bund: 9inch (22.86cm) pipe to drain, beyond pond*
- *Leaky debris dams: 8 to intercept and slow flow*
- *Floodplain restoration: reduced grazing and rough grassland generation of floodplain to increase hydraulic roughness, evapotranspiration losses and infiltration losses. Any other attenuation scheme that required earthworks (e.g. offline ponds) were not feasible because the area is designated ancient ridge and furrow under existing stewardship and therefore has to be preserved. Any alteration to the ridge and furrow could generate PIFs under existing stewardship.*

Figure 4.5 PGIS annotated base map, also known as community mapping (Forrester and Cindery 2016, McCall 2014). This map was annotated by the farmer and was able to provide local knowledge of sources and pathways for flooding, referring to reference events using flood memories, whilst also confirming what precise interventions and their design that would non-intrusive to the farming and business factors.

4.2.5 Pilot Farm Site: PGIS Digitised Farmer Input to Identify Problems

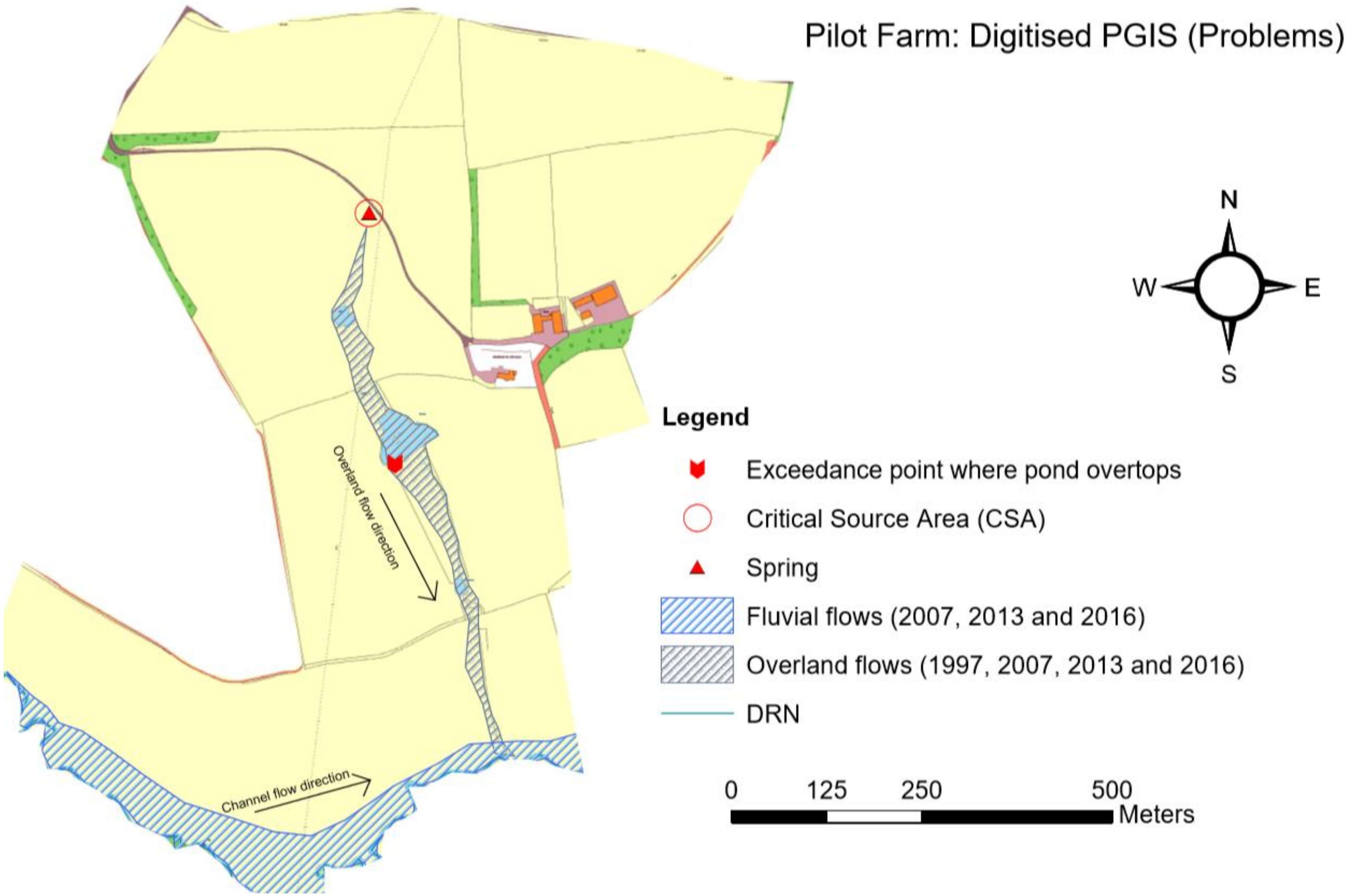


Figure 4.6 Digitised PGIS 'problems', outlining sources and pathways of flood flows. Extents provided for fluvial and pluvial flood flows, including the reference years those events occurred.

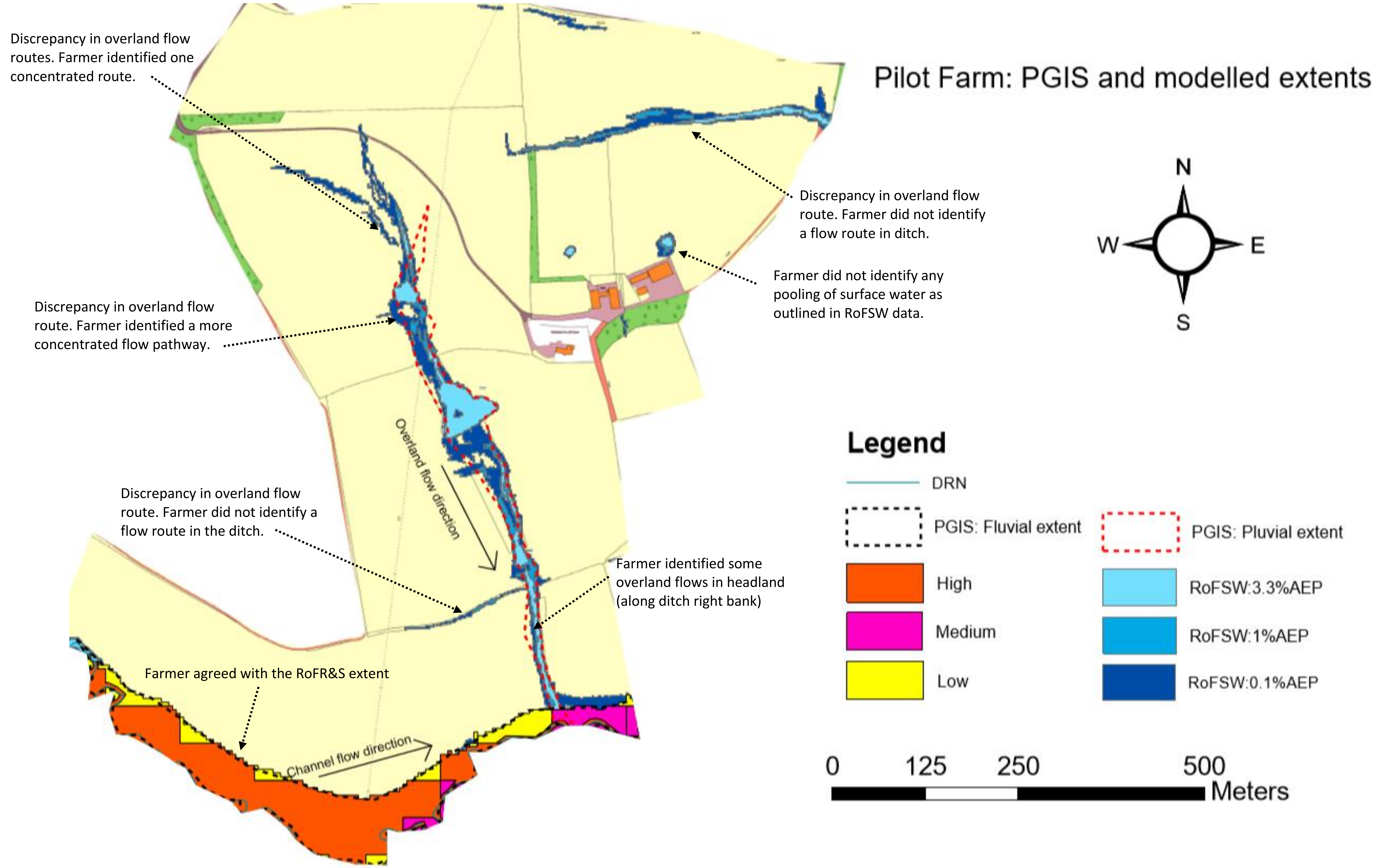


Figure 4.7 PGIS flood extents compared to Environment Agency modelled RoFSW (3.3%AEP, 1%AEP and 0.1%AEP) and RoFR&S (low, medium and high).

4.2.6 Pilot Farm Site: PGIS Farmer Input to Identify NFRM Opportunities

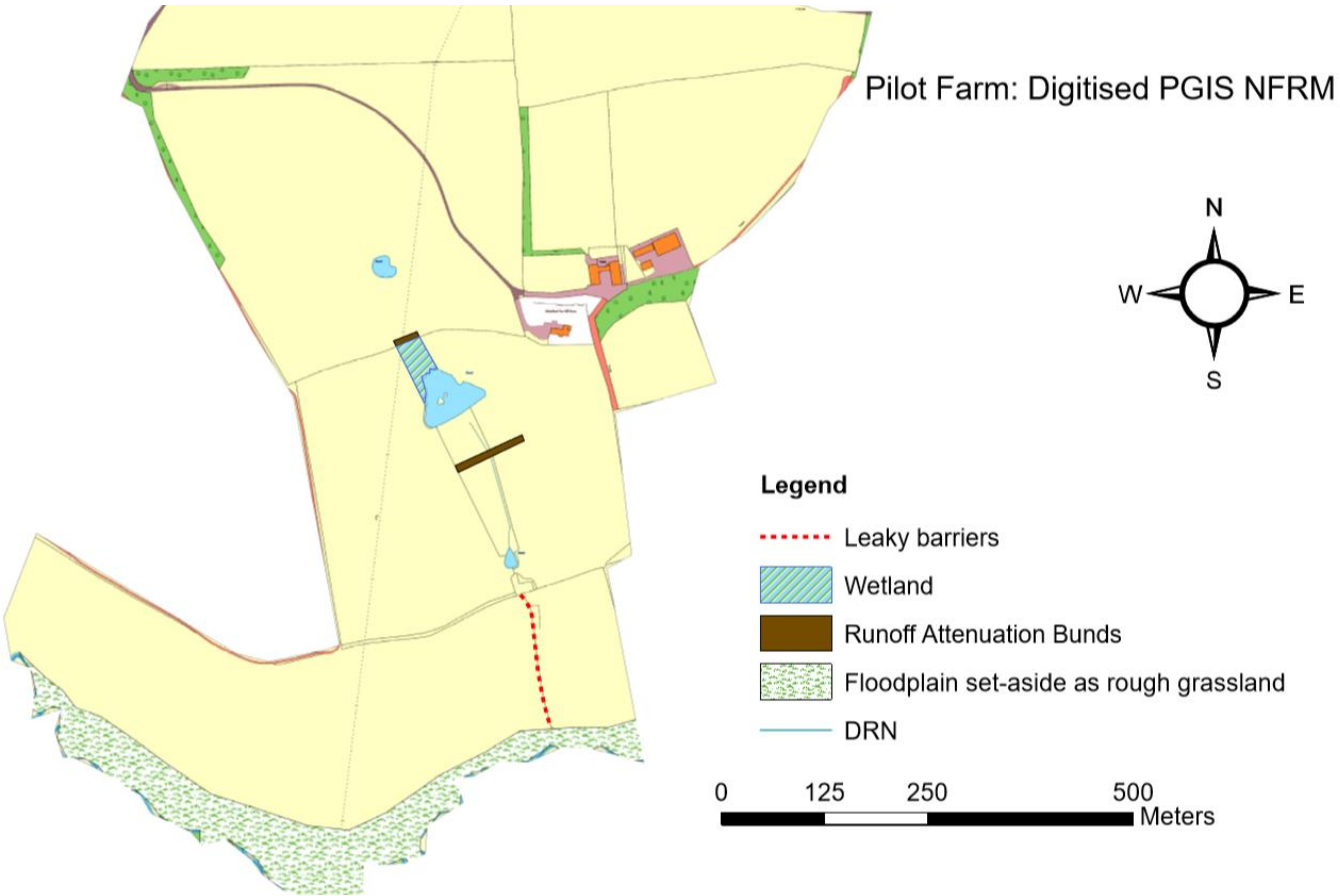


Figure 4.8 Digitised PGIS NFRM Opportunities

The PGIS framework applied to the pilot farm was able to facilitate the co-designing of a wide range of NFRM opportunities (Figure 4.8) at the site scale. Table 4.2 details the individual NFRM opportunities identified across the pilot farm investigation mapped in Figure 4.8, including their designed hydraulic function, area (m^2), and summary of storage volumes from attenuation features (m^3) derived from hydrological assessment and elevation values. These details were confirmed with the farmer upon completion of the final digitised map of the scheme to ensure full engagement during the whole design process. It must be noted, storage has not been calculated for hydraulic roughening opportunities, as per recommendations in Hankin *et al.* (2016a). Further detailed engineering designs would be required before the installation of any proposals. Table 4.2 outlines that the co-designed features total 1.81% of the farm area, 87.1% of which is due to the floodplain being set-aside as rough grassland. This is 3.19% lower than the 5% statutory requirement under the Common Agricultural Policy (CAP) Ecological Focus Area (EFA) requirements for Pillar II environment stewardship payments (see Chapter 2.2.3). However, the features intercept 100% of all fluvial and pluvial flows (Figure 4.8).

Table 4.2 Summary of co-designed NFRM opportunities, including hydraulic function, area and storage volumes (if any). Interventions listed from the top of the farm to the bottom (receiving watercourse).

NFRM opportunity	Hydraulic function	Area (m^2)	Storage volume (m^3)
Bund 1	Interception and attenuation of overland flood flows	120	260
Wetland	Increasing hydraulic roughness Interception and attenuation of overland flood flows	1,010	790
Bund 2	Interception and attenuation of overland flood flows	230	390
Leaky barriers	Increasing roughness and slowing overland flood flows in ditch feeding watercourse	20	N/A
Rough grassland	Increasing floodplain roughness, slowing overland and fluvial flood flows	9,330	N/A
TOTAL		10,710	1,440

4.3 Data Collection Review

Using both modelled layers, RoFSW (Figure 4.3b) and RoFR&S (Figure 4.3c), and the input provided by the farmer during the pilot PGIS exercise (Figure 4.5 and Figure 4.6), it is evident the farm conveys high levels of surface runoff into the receiving watercourse, Knee Brook. Analysis of the modelled RoFSW extents provided in the FIP indicates high levels of runoff in the centre of the farm through a valley, overtopping existing storage features (ponds) during the larger events; RoFR&S extent also provided in the FIP indicates a high level and frequent inundation of the floodplain.

However, on reviewing the FIP desk-based data, the PGIS exercise identified disparities in the RoFR&S and RoFSW data compared to the perceived flow routes and extents digitised in Figure 4.7 by the participant. The largest disparities were associated with the RoFSW extents, which are modelled on LiDAR attributed elevation at 2m resolution, homogenised roughness values based on Land Cover Map 2015 (LCM2015), and total rainfall across 91,000 tiles nationally across England and Wales. In the urban environment, buildings were raised by 0.3m to account for steps into properties, and roads lowered by 0.125m to reflect the gullying effect of surface water on roads (Moore *et al.* 2015). However, in rural environments these amendments were not made to properties, farm buildings and farm tracks, leading to often more variation in representation than an urban environment (Néelz and Pender 2015). This is reflected in Figure 4.7, in which the RoFR&S fluvial extents were considered largely representative by the farmer (± 0.3m variation across the floodplain), but the RoFSW inaccurate with a greater percentage coverage (+13.6%) than the flood flows and extents mapped by the farmer. Furthermore, where the RoFSW data identified three CSAs, the farmer considered there to be only one overland flow route during any high rainfall events. Total storage required for the 1%AEP (as recommended by the Environment Agency 2016d) was also calculated for the farm as part of the pilot. Using the Woods-Ballard *et al.* (2015) methodology (outlined in section 3.4) for a 0.59km^2 catchment area the total storage for the farm during a 1%AEP/12hr storm equates to 3060m^3. The co-designed NFRM attenuation features achieved 47.05% of this volume, but additional measures would be required to store all of the 1%AEP flood flows conveyed into the receiving watercourse.

4.4 Summary of Pilot Site Investigation

The pilot PGIS investigation successfully identified NFRM opportunities across the farm, informed by a risk-based approach, addressing the sources and pathways of flood flows that enter the receiving watercourse and come out of bank in flood conditions. The farmer was able to identify unproductive areas of land to situate runoff attenuation features (RAFs) for upstream attenuation. Table 4.2 shows the design specification of the co-designed NFRM opportunities (note these structures were designed to be normally dry but only active in spate conditions), with the aim of attenuating the peak with maximum distributed upstream storage through the duration of the event (Quinn *et al.* 2013a). Some NFRM techniques were considered more cost-effective for the farm and easier to implement than others. Features that integrated into the existing Stewardship arrangement, such as leaky barriers that do not create PIFs, were more acceptable than additional storage devices. The farmer was also able to 'ground truth' RoFSW and RoFR&S data by referring to specific events when flow pathways became active and from where (i.e. CSAs) - this was supported by photographic evidence of reference events (March 2016 and July 2007). With regards to the July 2007 event, the farmer commented that no matter how large the RAFs, the volume of overland flow was too large and rainfall too prolonged to address such an event (0.05%AEP according to Environment Agency 2008).

4.5 Upscaling PGIS Framework: Reviewing Farm Information Pack Data

When this methodology was upscaled, it was acknowledged that additional time for reconnaissance was also required, as the participant wanted to confirm these proposals in-situ with the maps from the FIPs. This verification process is critical to generating trust between the local stakeholder and the expert. By engendering trust, participants were likely to be more open and share their own knowledge as part of a collaborative approach to identifying problems and devising mitigation techniques (Maiden *et al.* 2017, McEwen and Jones 2012). Table 4.3 reviews the replicability and utility of the pilot datasets used in FIPs at the wider catchment scale, when undertaking additional PGIS exercises with farmers and landowners, identifying those that were more critical to the co-designed process.

Table 4.3 Replicability and utility of pilot farm data and techniques to wider catchment scale

Desk-based assessment technique	Replicability	Gaps (coverage and resolution)	Notes, amendments and utility for co-design
Physical characteristics			
LiDAR (DTM - 2m)	Y	Coverage: 63%, mostly lowlands, less in uplands Resolution: 2m resolution between x,y,z points	LiDAR merged with OS Terrain 5m DTM data for full coverage. This misses detail of smaller (<2m width) ditch profiles. On review, it was still considered useful to include to give an indication of the general topography, elevation and features in the landscape via the bare-earth DTM.
Detailed River Network (DRN)	Y	Coverage: Full coverage Resolution: Precision at watercourse centre line	Still provided, but to be delivered with a caveat of accuracy based on last update (2016).
Hydrology of Soil Types (HOST)	Y	Coverage: Full coverage Resolution: Largely homogenised cells at $1km^2$	Still provided, but to be delivered with a caveat of accuracy based on resolution. On review, less critical but still included as micro-scale changes in soil type was well noted by farmer.
Superficial geology	Y	Coverage: Full coverage Resolution: Largely homogenised cells at $1km^2$	Still provided, but to be delivered with a caveat of accuracy based on resolution. On review, less critical but still included as micro-scale changes in geology and infiltration was well noted by farmer.
Land Cover Map (LCM) 2015	Y	Coverage: Full coverage Resolution: $25m^2$ cell values	Still provided, but to be delivered with a caveat of accuracy based on resolution. Less critical, farmer was very familiar with land coverage.

Historic Land Cover (1906 - 1936)	Y	Coverage: Full coverage Resolution: Map scaled at 1:2000	Key features (e.g. ponds, old river lines) to be highlighted and labelled to provide explanation. On review, a critical dataset to indicate pre agricultural intensification features and watercourse lines to help guide opportunities around 'restoration'.
Hydrological characteristics			
SCIMAP Hydrological Connectivity	Y	Coverage: Full coverage Resolution: $5m^2$ cell values based on DTM used	Still provided, outlining key flow pathways and connectivity to receiving watercourses. On review, a critical DSM to indicate hydrological connectivity across the landscape, guiding focus on sources and pathways of flood flows across the landscape.
RoFSW (3.3%, 1% and 0.1%AEP)	Y	Coverage: Full coverage Resolution: $5m^2$ cell values based on DTM used	Still provided, useful extents in outlining surface water pathways, with the need to refer to AEP in terms of event size and frequency. The most critical dataset to guiding discussion of targeted runoff attenuation across the landscape to high detail, also accounting for the magnitude of the flood events.

RoFR&S (low, medium and high)	Y	Coverage: Full coverage Resolution: 5m^2 cell values based on DTM used	Still provided, useful extents in outlining river flood extents, with the need to amend bandings to AEP (as below). Low = 0.1% - 1%AEP Medium = 1% - 3.3% AEP High = > 3.3% AEP On review, lower spatial resolution than the RoFSW dataset, but provides an indication of fluvial extents in relation to event magnitude.
WFD Ecological Status	Y	Coverage: Full coverage Resolution: Based on EA waterbody ID classes	Still provided, with a caveat of this data based on continuous monitoring of stream influenced by multiple farms. On review, this data does not provide any targeted indication of NFRM measures, however, still included to outline need to address diffuse agricultural runoff.
Water Management Issues	Y	Coverage: Full coverage Resolution: Based on EA waterbody ID classes	Still provided, with a caveat of this data based on continuous monitoring of stream influenced by multiple farms. On review, like the WFD ecological status this data does not provide any targeted indication of NFRM measures, however, still included to outline need to address diffuse agricultural runoff.

Social characteristics			
ALC (poor - excellent)	Y	Coverage: Full coverage Resolution: Largely homogenised cells at $1km^2$	Still provided (particularly for constraints and sensitivities around high grade ALC), with a caveat of accuracy as this data is based on MAFF (1988) classifications. On review, considered a useful dataset to give a high level indication of agricultural land value to the farmer.
Living Landscape Strategy areas	Y	Coverage: Full coverage Resolution: Based on Wildlife Trust boundaries	Still provided (particularly for constraints and sensitivities around NFRM types), with a caveat of the length of the strategy (until 2025). Less critical dataset for problem identification, but provides some insight into NFRM opportunities that are in keeping the character of the area.
Existing and targeted stewardship	Y	Coverage: Full coverage Resolution: Based on RPA boundaries	Still provided (particularly for constraints and sensitivities around NFRM types and locations), with care taken to differentiate between Environmental and Countryside Stewardship. On review, farmer considered this to be a crucial consideration to ensure any NFRM opportunities are not the detriment of existing stewardship areas and capital items.

4.6 Chapter summary

The pilot study applied within the Knee Brook sub-catchment was able to test to robustness and assess replicability of the co-design approach, along with the utility of the datasets used in the FIPs. The pilot method was able to successfully co-design runoff attenuation features, leaky barriers and set the floodplain aside as rough grassland by reducing grazing practices. It is important to note that the method was not trying to passively engage the farmer in order to 'approve' a scheme, but rather co-produce knowledge of flood risk sources and pathways using tactile flood memories and the FIPs to co-design an 'acceptable' NFRM scheme (full catchment scale results provided in chapter 5).

The pilot enabled lessons to be learnt of the co-design framework and datasets within the FIP that can be noted when upscaling the process across the whole catchment area. Key lessons include, the need to provide sufficient ground-truthing time with FIP data and NFRM opportunities. In regards to the FIP data, the hydrology datasets (in particular RoFSW and SCIMAP) were particularly useful in identifying sources and pathways of flooding. Historic land cover also gave an historic reference for any restorative faring practices, compared to the current land cover map (LCM2015) that was less useful.

5 PGIS Results: NFRM Opportunities

5.1 Introduction

This chapter addresses the second aim, to co-design and evaluate recommendations of mapped NFRM opportunities across the total catchment area, employing the PGIS method reviewed in section 4. Section 5.2 details and evaluates the co-designed NFRM opportunities visually and statistically, using the rules defined in section 3.4 and demonstrated in section 4, in order to meet objectives 2.3 and 2.4. Finally, the influential factors to the citing of NFRM opportunities will also be analysed in section 5.3, to better understand the local motivations and constraints for adopting NFRM. This enables agencies and strategic FRM authorities to better understand what types of NFRM, and in which locations they are more adoptable for farmers and landowners.

5.2 NFRM Opportunities

Across the total catchment area, 487 NFRM opportunities were individually co-designed with all landowners and farmers using the PGIS framework (overview provided in Figure 5.1). Each feature was allocated a GIS shape, line or point file reference, relating to a spreadsheet of all proposals and their 12-figure national grid reference (see Appendix - E). These schemes fell into three categories of WwNP across fluvial catchments (section 2.3 for further details):

1. **Runoff Management**: Features addressing the sources and pathways of overland flow routes, employing a variety of features to slow, store, filter and disconnect runoff routes, including, bunds, ponds, sediment traps, swales, logjams and cross-drains. Soil and land management practices encouraging rainwater harvesting and improved soil heath for permeability also address runoff issues at the source.
2. **River and Floodplain Management**: Features and changing land use to encourage a slow flood wave propagation through the river network. This aims to encourage natural stream and floodplain processes. Methods include the introduction of leaky barriers in-stream to slow the flood peak, with earlier and greater connection of the floodplain to enhance storage with offline ponds and storage areas, and morphological river alteration, including re-meandering and bank lowering.
3. **Woodland Management**: Undertaking afforestation in targeted areas to intercept flow routes and out of bank flows by increasing the hydraulic roughness, encouraging permeability by the establishment of deep rooting deciduous species and evapotranspiration losses with broadleaved canopies. Locations for woodlands include across slopes, in the floodplain and riparian areas, as well as infilling or planting hedgerows, and making field boundaries larger and more established. Management also includes thinning practices to encourage undergrowth and using woody material on the woodland floor to intercept flow pathways on bare woodland floor.

Table 5.1 specifies the number and types of proposals in each delineation and their primary function, as agreed by landowners/farmers, and informed by wider consultees during the PGIS exercises. Figure 5.3 provides the breakdown of interventions across the catchment area (see Appendix E for reference to calculating number of interventions) based on the key themes. The most commonly identified NFRM features were forms of runoff management (58%), followed by river and floodplain management techniques (35%), and lastly woodland management, including riparian, floodplain and wider catchment afforestation (7%).

Runoff management techniques were mostly identified in the headwaters and areas of high flow accumulation, with runoff attenuation features (bunds, ponds, swales, sediment traps and track drainage alteration) the most identified type of runoff management techniques (89%). Runoff management that involved wider change in land management practices (soil aeration and conservation tillage) and areas for cultivation (buffer strips and winter crop cover) were least preferable (11%). River and floodplain management techniques were mostly identified in mid-lower reaches of the catchment, where the channel could more readily connect to the floodplain. The most popular techniques identified include offline storage (44%) and in-channel leaky barriers (41%). Schemes that require morphological channel alteration (online storage, floodplain restoration and river restoration) comprised of 15.11% of all river and floodplain management opportunities. Woodland management techniques comprised of afforestation and altered management of existing woodlands, to generate woodland water retention areas (wet woodlands). The latter was the most identified woodland management opportunity across the catchment (61%), followed by reintroducing or connecting hedgerows (19%), and cross-slope woodlands (10%). Only one farm identified an area for a catchment woodland (3%), and one other identified an area for a riparian and floodplain woodland (6%). Section 5.4 analyses the physical, hydrological and social factors influence in greater detail, testing for any association between NFRM technique and locations.

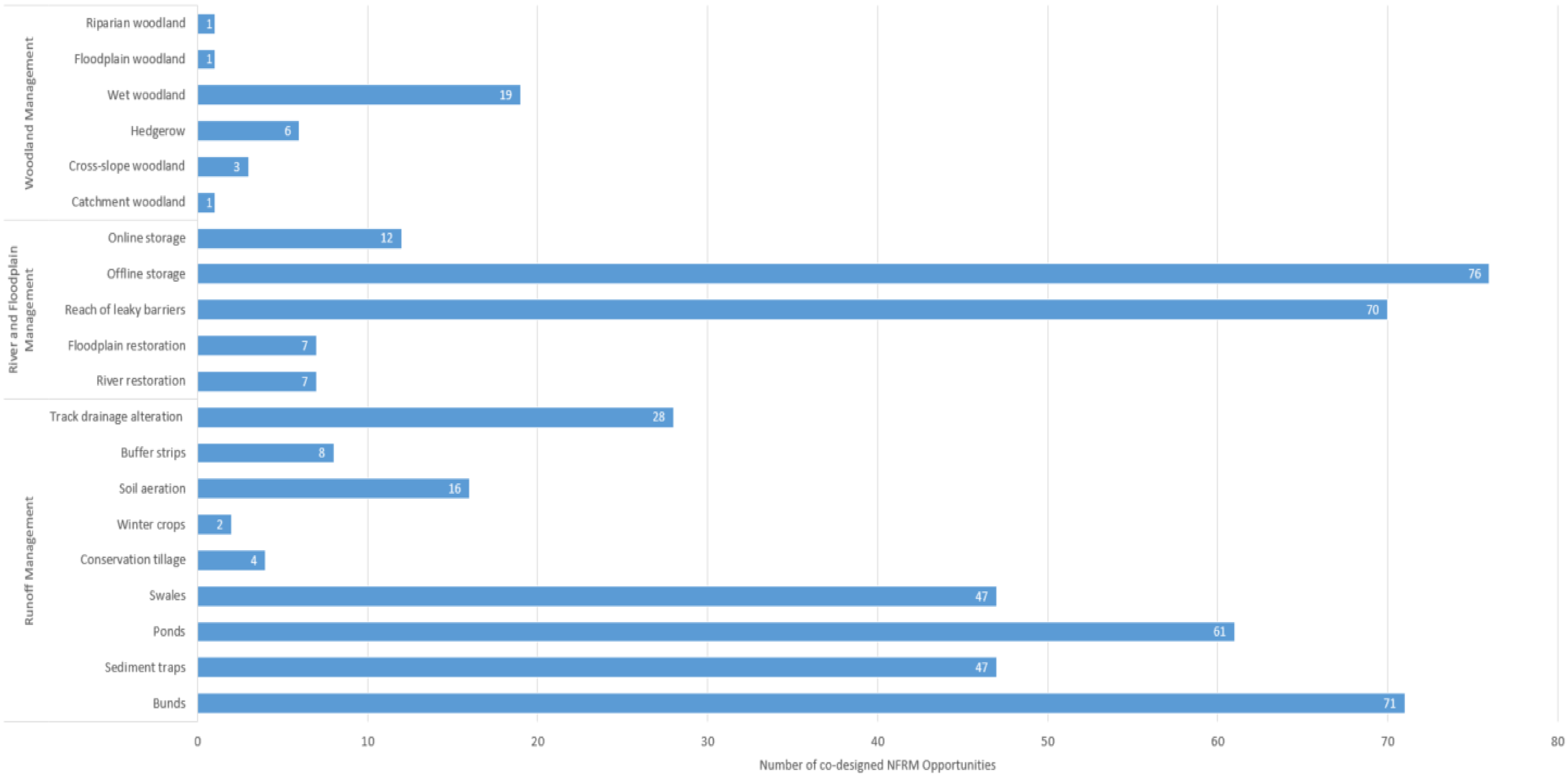


Figure 5.1 NFRM opportunities across the catchment, breakdown based on types of interventions in dominant WwNP themes. Details of the NFRM opportunities are given in Appendix E. All NFRM opportunities are based on those provided in FIPs to inform the PGIS exercise (see Appendix C) with definitions, example images and design schematics. The terms for the NFRM features used are detailed and expanded are those given in Table 2.7 to ensure a consistency in the description of techniques.

Table 5.1 Tabulated NFRM opportunities, delineated to sub-catchment area codes outlined in section 3.3.

RUNOFF MANAGEMENT						**RIVER AND FLOODPLAIN MANAGEMENT**								**WOODLAND MANAGEMENT**				
Bunds	Sediment traps	Ponds	Swales	Soil aeration	Riparian margins	Re-meandering	Bank lowering	Leaky debris	Offline storage	Online storage	Watercourse fencing	Arable reversion	Wetland creation	Hedges	Slope woodland	Floodplain woodland	Riparian woodland	Wet Woodland
KNEE BROOK TRIBUTARIES (87km²)																		
CAM - REACH: SP 12399 36822 → SP 14863 39005 (SIZE: 6.1km²) *(KB_1)*																		
X								X		X				X				
KNEE BROOK (1ST ORDER STREAM) – REACH: SP 19386 42375 → SP 18628 39070 (SIZE: 9.4km²) *(KB_2)*																		
X			X					X									X	X
KNEE BROOK (1st ORDER STREAM) – REACH: SP 18165 42276 → SP 17151 39498 (SIZE: 7.2km²) *(KB_3)*																		
		X						X	X									
CAMPDEN DITCH – REACH: SP 14982 36652 → SP 16183 38483 (SIZE: 4.9km²) *(KB_4)*																		
X					X			X		X				X				
BLOCKLEY BROOK – REACH: SP 16278 33316 → SP 18722 36661 (SIZE: 14.1km²) *(KB_6)*																		
	X	X				X	X	X	X				X	X				X
MARBROOK – REACH: SP 16370 36648 → SP 18308 37433 (SIZE: 8.4km²) *(KB_5)*																		
X								X										X
ASTON MAGNA DITCH – REACH: SP 20352 34555 → SP 20939 36055 (SIZE: 5.4km²) *(KB_8)*																		
	X		X	X														
PADDLE BROOK – REACH: SP 21044 39364 → SP 23067 37199 (SIZE: 8.1km²) *(KB_9)*																		
X	X	X						X	X		X		X			X		X
STRETTON-ON-FOSSE DITCH – REACH: SP 22375 39449 → SP 23521 37239 (SIZE: 7.8km²) *(KB_10)*																		
								X										
KNEE BROOK DOWNSTREAM CONFLUENCE (3RD ORDER STREAM) – REACH: SP 18270 37684 → SP 21818 36357 (SIZE: 7.1km²) *(KB_14)*																		
X					X				X			X					X	X

KNEE BROOK FURTHEST DOWNSTREAM (4^{TH} ORDER STREAM) – REACH: SP 21921 36336 → SP 25822 37879 (SIZE: 8.5km^2) *(KB_14)*																	
				X				X				X				X	
NETHERCOTE BROOK TRIBUTARIES (37.3km^2)																	
NETHERCOTE BROOK (1^{ST} ORDER STREAM) - REACH: SP 31912 33969 → SP 28883 33109 (SIZE: 7.9km^2) *(NB_1)*																	
X		X		X				X	X				X		X		
SOUTH HILL DITCH – REACH: SP 28493 31189 → SP 28989 31785 (SIZE: 2.5km^2) *(NB_2)*																	
	X	X	X	X					X			X	X				
GREAT WOLFORD DITCH – REACH: SP 23342 32700 → SP 25842 36500 (SIZE: 9.3km^2) *(NB_3)*																	
		X					X										X
STANFORD BROOK – REACH: SP 24920 31796 → SP 25915 33630 (SIZE: 5.5km^2) *(NB_8)*																	
X		X	X				X				X	X					
NETHERCOTE BROOK DOWNSTREAM (3^{RD} ORDER STREAM) – REACH: SP 27966 33146 → SP 26300 37061 (SIZE: 12.1km^2) *(NB_9)*																	
		X						X								X	
RIVER STOUR TRIBUTARIES (58km^2)																	
SUTTON BROOK- REACH: SP 34277 40518 → SP 30325 37342 (SIZE: 12.8km^2) *(SB_1 – 5)*																	
X	X	X	X	X	X	X	X			X		X		X	X		X
UPSTREAM RIVER STOUR (1^{ST} ORDER STREAM) – REACH: SP 38181 35520 → SP 31660 36493 (SIZE: 25.8km^2) *(RS_6 – 7)*																	
X		X		X	X		X	X	X		X		X		X		X
DOWNSTREAM RIVER STOUR (3^{RD} ORDER STREAM) – REACH: SP 31366 36433 → SP 26415 37095 (SIZE: 19.4km^2) *(RS_8 – 10)*																	
				X		X		X			X					X	
PIG BROOK (5.7km^2)																	
PIG BROOK – REACH: SP 23880 38962 → SP 26468 39598 (SIZE: 5.7km^2) *(PB_1 – 3)*																	
	X	X	X	X			X	X		X			X	X			X

In addition to the total number of NFRM opportunities and their locations outlined in Table 5.1, Figure 5.2 outlines the total upstream area utilised and the attenuation volume associated with the co-designed NFRM opportunities across each delineation. These values have been identified adhering to the rules demonstrated in section 4.2.6, in which NFRM techniques have been classified based on their land take and volume of attenuation. Figure 5.2 indicates a weak 0.34 p-value correlation between area coverage and volume attenuated by each delineation's NFRM techniques. This differs to other NFRM studies that have considered the coverage and storage of interventions, for example, the Belford scheme identified greater volumes of attenuation with an increased number of larger runoff attention features, such as ponds and bunds, which provides storage for peak flood flows (Quinn *et al.* 2016). However, the weak correlation could be due to the types of NFRM techniques that have been identified and their potential storage capacity. Leaky barriers for example, were the most commonly co-designed intervention, however, these techniques were defined as providing no storage, but increasing hydraulic roughness in, and some instances adjacent to, the channel.

Soil and land management methods, such as arable reversion techniques and conservation tillage, have a large area coverage (when applied), but do not provide storage and are primarily applied to increase hydraulic roughness. Woodland management methods, particularly wet woodlands that were frequently co-designed during the PGIS exercises (Figure 5.1), also have a larger area coverage with no allocated additional storage, but increased hydraulic roughness of the woodland floor. It is conceivable that greater classification of storage associated with individual measures in guidance documents, such as the Scottish Rural SuDS guidance (Duffy *et al.* 2016) and the Environment Agency's catchment map and model guidance (Hankin *et al.* 2016a) would enable greater confidence in applying reviewed values of storage to NFRM techniques.

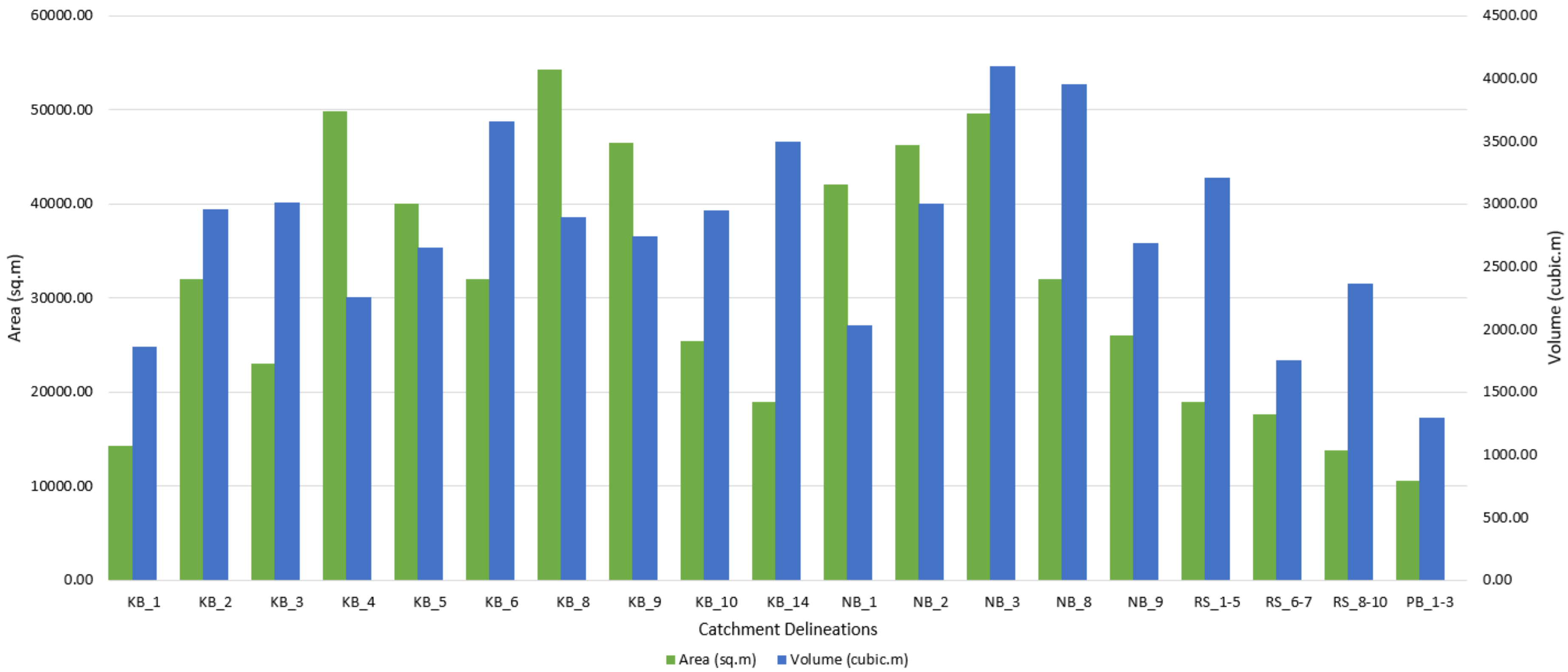


Figure 5.2. Total upstream area (m^2) and attenuation volume (m^3) attributed to the co-designed PGIS - NFRM opportunities.

Given the high number of diverse NFRM opportunities, Figure 5.3 provides an overview of the different useable areas for different opportunities outlined in section 3.3, with each intervention assessed to different desk-based constraints. For interventions applied out-of-channel (e.g. storage areas, woodlands, buffer strips etc.) values are provided as a percentage of whole catchment area (187km^2); for interventions applied and altering in-channel morphology (e.g. leaky barrier, river re-meandering) values are provided as a percentage of the total reach of all watercourses as measured according to the DRN (68.02km). This analysis indicated that the most limited capacity is available for riparian woodlands (4.6%), which is only applicable in areas ≤ 50m of a watercourse; whereas, leaky barriers were the most applicable NFRM techniques across the DRN (63.9%).

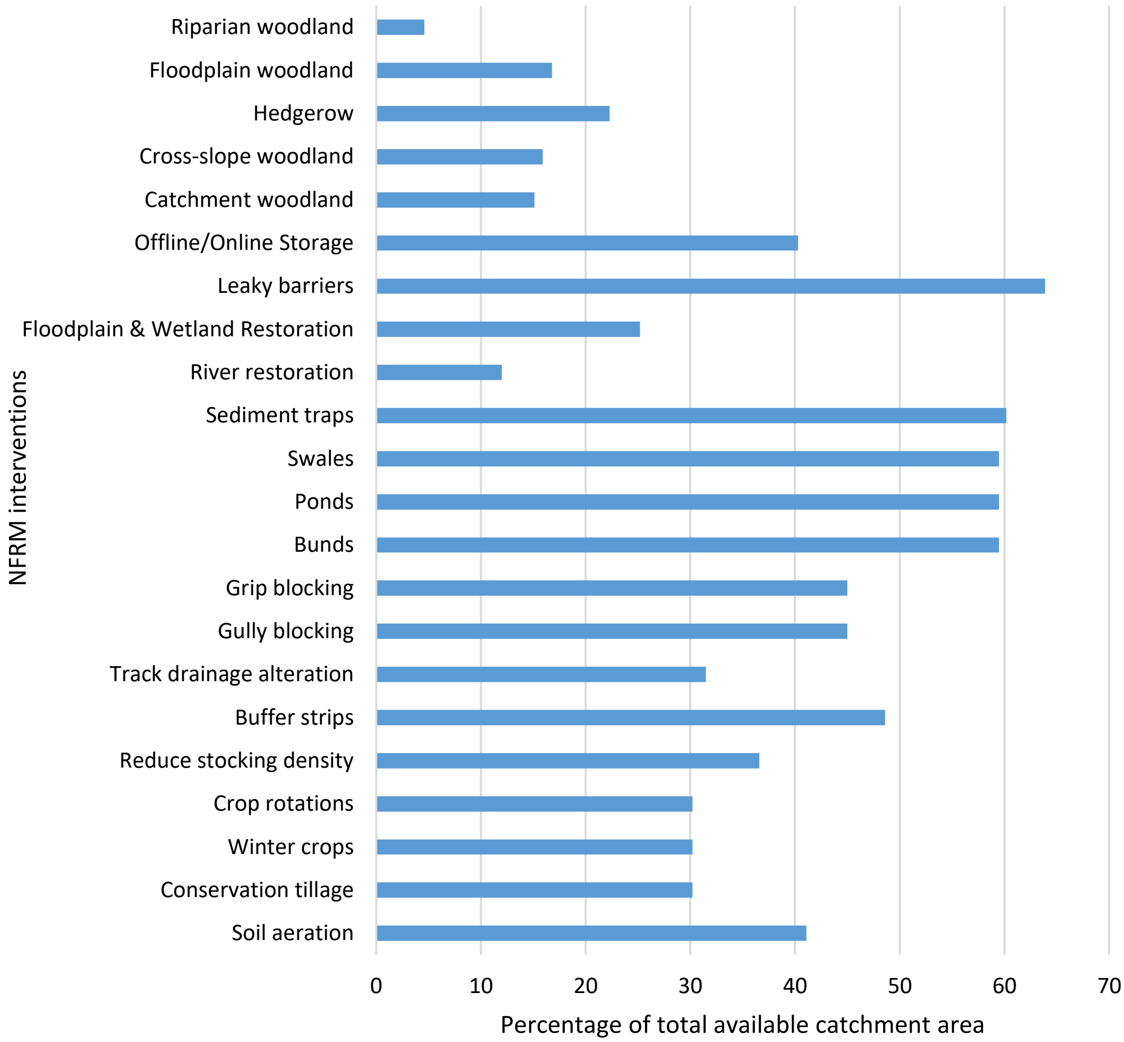


Figure 5.3 Overview of useable catchment area and river channel network for NFRM opportunities, method for calculating available catchment area outlined in Section 3.5, Figure 3.20

Comparing these results to Figure 5.1 (total NFRM opportunities), it is evident these available areas identified from the constraints masking layer closely relate to the number of opportunities for different interventions, with 70 reaches of leaky barriers co-designed and only one area of riparian woodland across the total 'useable' catchment area. In addition to areas of constraints (where NFRM is not suitable), sensitivities where identified through the PGIS exercises. Sensitivities were areas unsuitable for NFRM, but must be carefully considered due to possible detrimental implications such as significant loss of income by applying NFRM in Grade 1 Agricultural Land or drastically changing the landscape within an AONB according to its relevant landscape strategy (Cotswold AONB 2016).

During the PGIS exercises, it was identified that areas of existing stewardship must also be sensitively considered for any NFRM opportunities (as recommended by Holstead *et al.* 2015). Under the Common Agricultural Policy (CAP), any recipient of environment stewardship (under Higher Level, Entry Level or Organic Entry Level up to 2020, and Countryside Mid-Tier or High-Tier up to 2025) must not generate any permanent ineligible features (PIFs) to adhere to payment conditions under Pillar II requirements. PIFs are defined as "areas of land significantly altered from the requirements within the stewardship scheme" (EU 2015). Therefore, of the 64.9% of the catchment under some form of environmental stewardship, NFRM opportunities must be co-designed in compliance with stewardship requirements, and not in a manner that could result in fines to the stewardship recipient (farmers and landowners) on inspection from the Rural Payments Agency (RPA). The Knee Brook contained the largest number of farms under environmental stewardship, with the majority of farms and estates within the sub-catchment under Entry Level Stewardship (66.2%). Only 12.6% of farms and estates were under Countryside Stewardship, the stewardship scheme superseding Environmental Stewardship. The implications of these policy influenced design considerations are discussed further in Section 5.4, along with an evaluation of all influential factors that led to the situating of different NFRM opportunities to better understand the local motivations and constraints for adopting NFRM, and in what particular locations are they most suited.

5.3 Influential Factors

This section explores the role of physical, hydrological and social factors that influenced the situating of NFRM opportunities across the catchment, outlined in Table 5.2. This section analyses the relationship between these factors and the type and number of PGIS-NFRM techniques co-designed across the total catchment area.

Table 5.2 Summary of figures for influential physical, hydrological and social factors in order to determine the relationship between NFRM and these factors, with associated methodology

Influential factors	Methodology	Result figure
Physical Characteristics		
Strahler stream ordering	3.4	5.4
Geology	3.4.1	5.5
Pedology	3.4.2	5.6
Land cover	3.4.3	5.7
Hydrological Characteristics		
Risk of Flooding from Surface Water (RoFSW)	3.4.7	5.8
Risk of Flooding from Rivers and Sea (RoFR&S)	3.4.8	5.9
WFD ecological status of watercourse	3.4.5	5.10
Social Characteristics		
Agricultural Land Classification (ALC)	3.4.9	5.11
Land Use*	-	5.12
Participant typology *	-	5.13
Stewardship*	-	5.14

**Characteristics have not been obtained through desk-based characterisation and therefore not presented in the associated methodology chapter. These characteristics have been obtained meeting the second aim as part of the PGIS exercise with landowners and farmers.*

5.3.1 Physical Factors

This section analyses the relationship between physical factors and NFRM opportunities, and presents these results in Figure 5.4 to Figure 5.7. The relationships have identified pertinent factors that have influenced the uptake of NFRM opportunities, which could assist other NFRM schemes in prioritising engagement and delivery where it is most adoptable based on desk-based physical characteristics. Nonetheless, no single physical factor emerged as the principal spatial influence for situating NFRM.

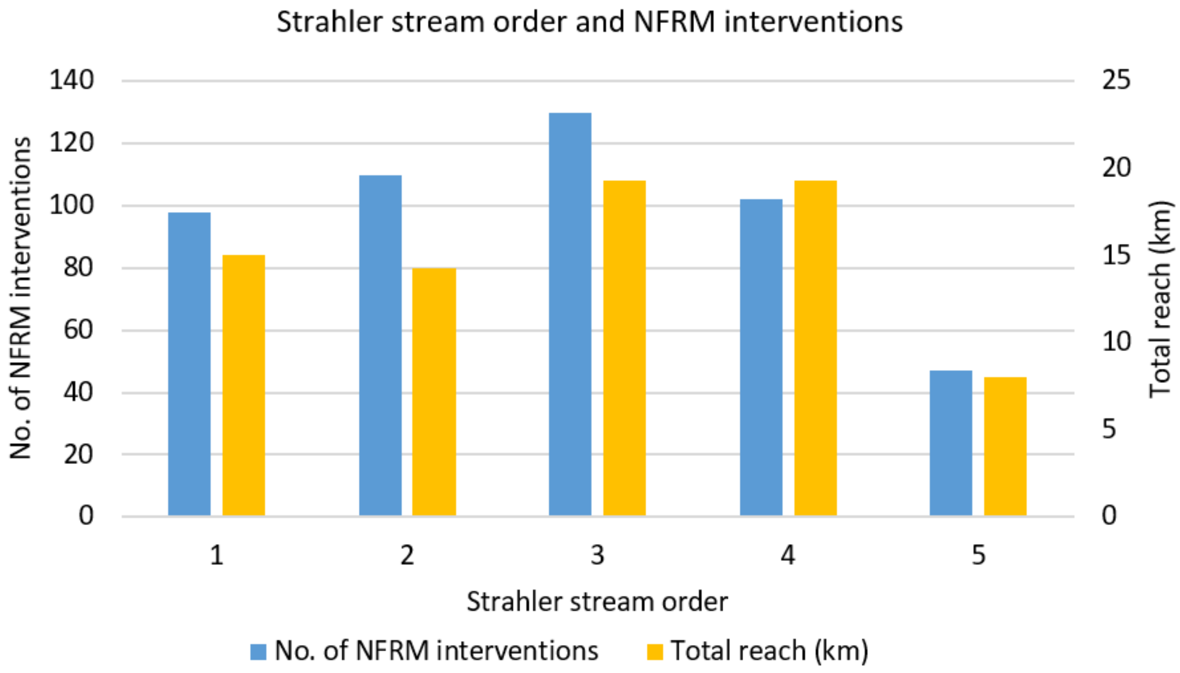


Figure 5.4 Relationship between Strahler stream order and NFRM opportunities

Figure 5.4 outlines Strahler three order streams were the most popular location for NFRM opportunities (26.69%). However, as a general pattern more NFRM was co-designed in the headwaters of the catchment in high order (1 – 2) streams (42.71%) than in the lowlands low order (4 – 5) streams (30.59%). The 12.12% difference between NFRM opportunities in the headwaters and lowlands is reflected in the types of NFRM techniques that have been co-designed during the PGIS exercise, with more runoff management and headwater river management techniques co-designed than larger offline storage and river restoration techniques more commonly applied in the lowlands (section 5.4).

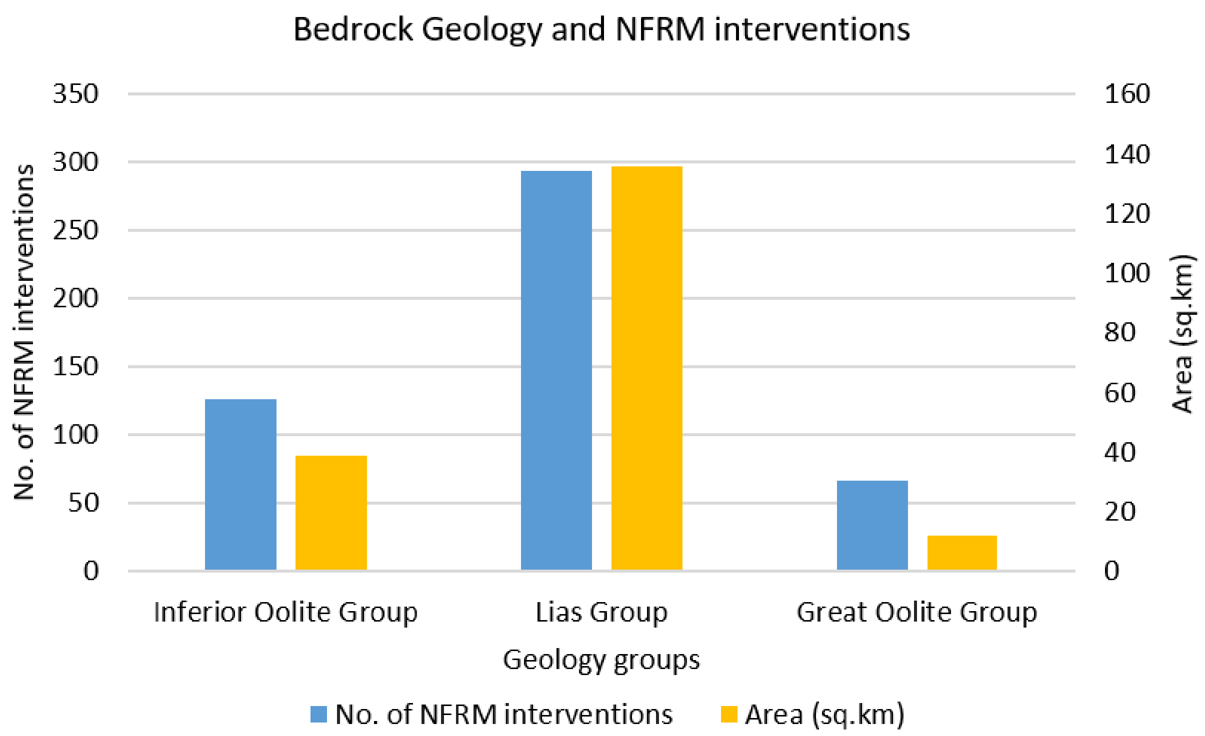


Figure 5.5 Relationship between geological classes and NFRM opportunities

Figure 5.5 outlines the Lias group of mudstone, siltstone, limestone and sandstone to be the most popular geological attribute for NFRM opportunities (60.36%). This group is associated with a limited capacity for infiltration, unlike the Oolite groups of porous limestone cast. However, coverage of geological groups is also significant in understanding the influence of this physical characteristics. The Lias group had the largest spatial coverage across the catchment, with 61.49% (particularly in the lowlands), and limestone Oolite groups had a smaller coverage (38.51%) across the headlands as part of the Cotswold escarpment. Further details of geological characteristics are provided in section 3.3.

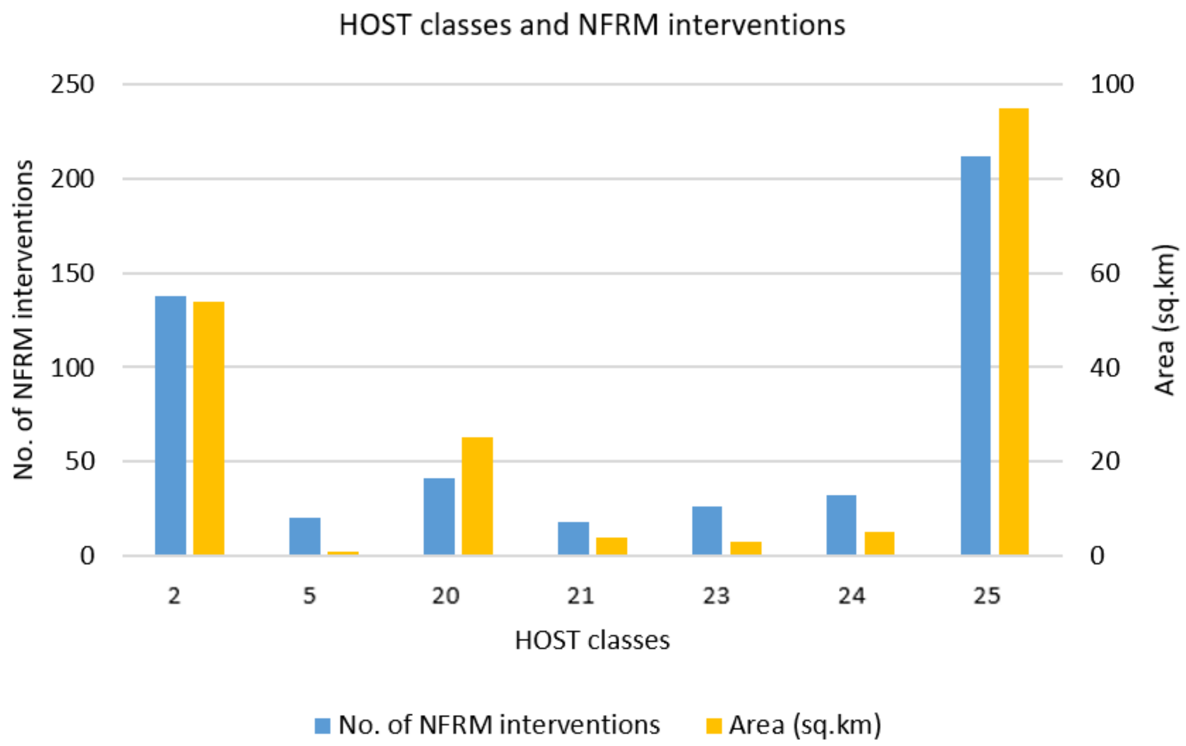


Figure 5.6 Relationship between HOST classes and NFRM opportunities

Figure 5.6 outlines that the majority of NFRM opportunities were co-designed in areas of impermeable or slowly permeable gleying clays (63.63%), which also comprised the largest catchment coverage of the study site (62.12%). Free draining soils (HOST class 2 and 5) comprised of the remaining 37.88% of the catchment area, and accounted for 36.37% of the co-designed NFRM opportunities. Whilst a high capacity of infiltration is often considered favourably for desk-based NFRM opportunity mapping studies (e.g. SEPA 2016 and Hankin *et al.* 2016a), Figure 5.6 indicates there was no clear relationship between pedological characteristics and the ability to situate NFRM opportunities. Further details of pedological characteristics are provided in section 3.3.

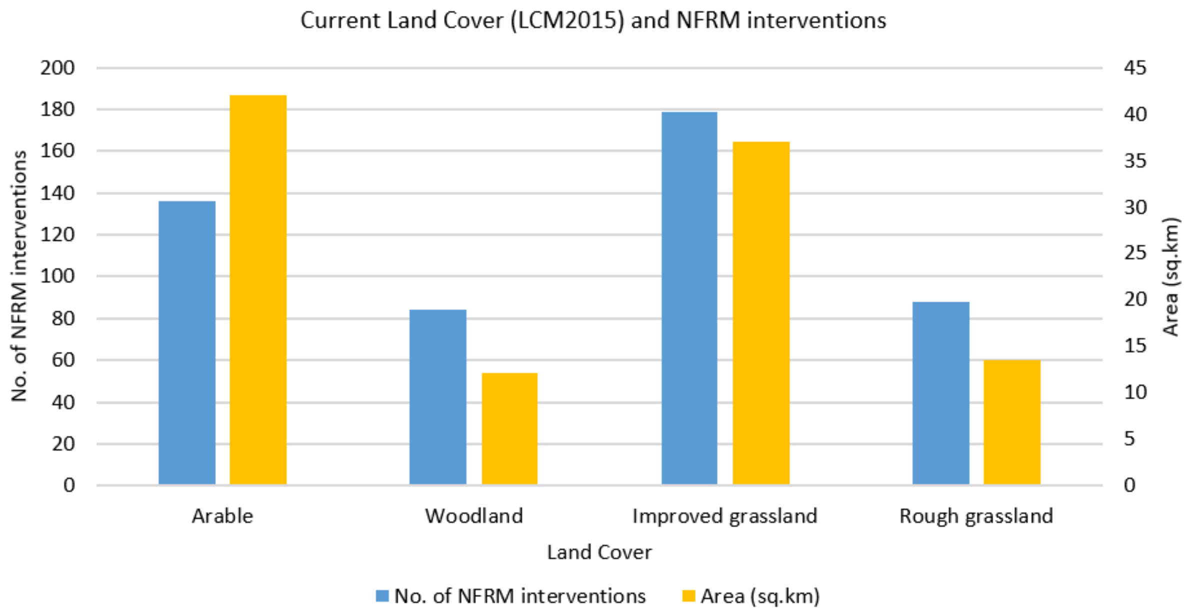


Figure 5.7 Relationship between Land Cover classes and NFRM opportunities

Figure 5.7 outlines that a high percentage of NFRM opportunities were co-designed in areas of improved grassland (36.75%) and arable crop growth (27.92%). The areas were also comprised of the largest land coverage across the catchment area at 37% and 42% respectively. This indicates NFRM opportunities were more readily co-designed in pasture farms, as opposed to arable, in which reversion or changes to arable land use were less popular. Holstead and Kenyon (2017) also reflected this pattern in NFRM workshops with farmers, who identified that arable drainage practices are to predominantly move the water off the landscape, not retain it. Therefore, any drainage practices that could conceivably alter these historic practices are considered less desirable. Further details of land cover characteristics are provided in section 3.3.

5.3.2 Hydrological Factors

This section analyses the relationship between hydrological factors and NFRM opportunities, with results presents in Figure 5.8 to 5.10. The relationships have identified pertinent factors that have influenced the uptake of NFRM opportunities, which could assist other NFRM schemes in prioritising engagement and delivery where it is most adoptable based on desk-based hydrological characteristics. No single hydrological factor emerged as the primary influence for situating NFRM.

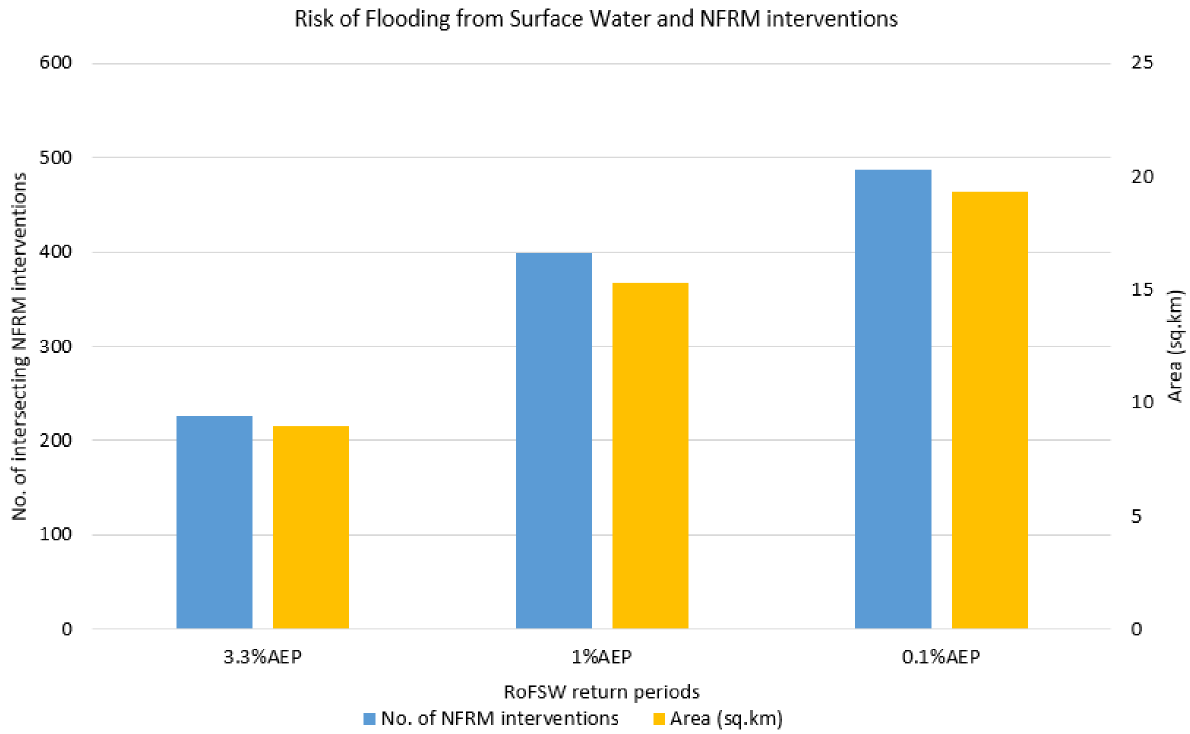


Figure 5.8 Relationship between RoFSW return periods and NFRM opportunities

Figure 5.8 demonstrates that the largest RoFSW flood extent (0.1%AEP) intersects all NFRM opportunities. The second largest event (1%AEP) intersects 81.72% of all NFRM opportunities and the smallest event (3.3%AEP) intersects 46.41% of all NFRM opportunities. This demonstrates a positive relationship between NFRM opportunities and the size of the flood extent, in principle, the larger the extent, the more NFRM opportunities are co-designed to intersect those flood flows in the co-design process. It is important to note that the RoFSW layers depicts the same flood routes to differing extents, in which the 0.1%AEP intersects all of the same NFRM opportunities as the 1%AEP and 3.3%AEP. Further details of the catchments flood risk characteristics are provided in section 3.3

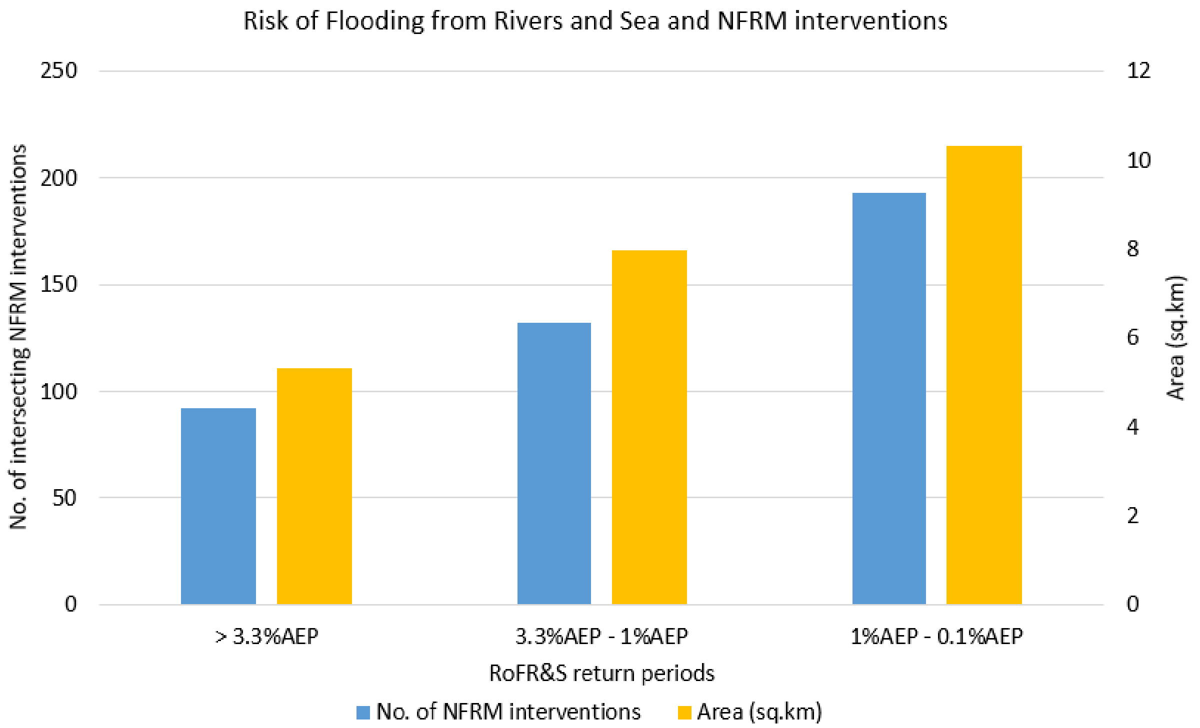


Figure 5.9 Relationships between RoFR&S return periods and NFRM opportunities

Figure 5.9 demonstrates that the largest fluvial flood extent (1%AEP - 0.1%AEP) intersects 39.63% of NFRM opportunities. The second largest fluvial extent (3.3%AEP - 1%AEP) intersects 27.10% of NFRM opportunities, and the smallest event and fluvial flood extent (>3.3%AEP) intersects 18.89% of the NFRM opportunities. This pattern outlines a strong relationship between the number of NFRM opportunities and the size of the flood extent; in principle, the larger the extent, the more NFRM opportunities are co-designed to intersect those fluvial flood extents in the co-design process. It is important to note that the RoFR&S layer depicts the same flood routes to differing extents; in which the 0.1%AEP intersects all of the same NFRM opportunities as the 3.3%AEP. Unlike the RoFSW layers that covers flood flows outside of the floodplain and into channel, the RoFR&S layer only represents extents from the channel into the floodplain. Therefore, the total catchment coverage is greater of the RoFSW extents in comparison to RoFR&S layer. Further details of the catchments flood risk characteristics are provided in section 3.3.

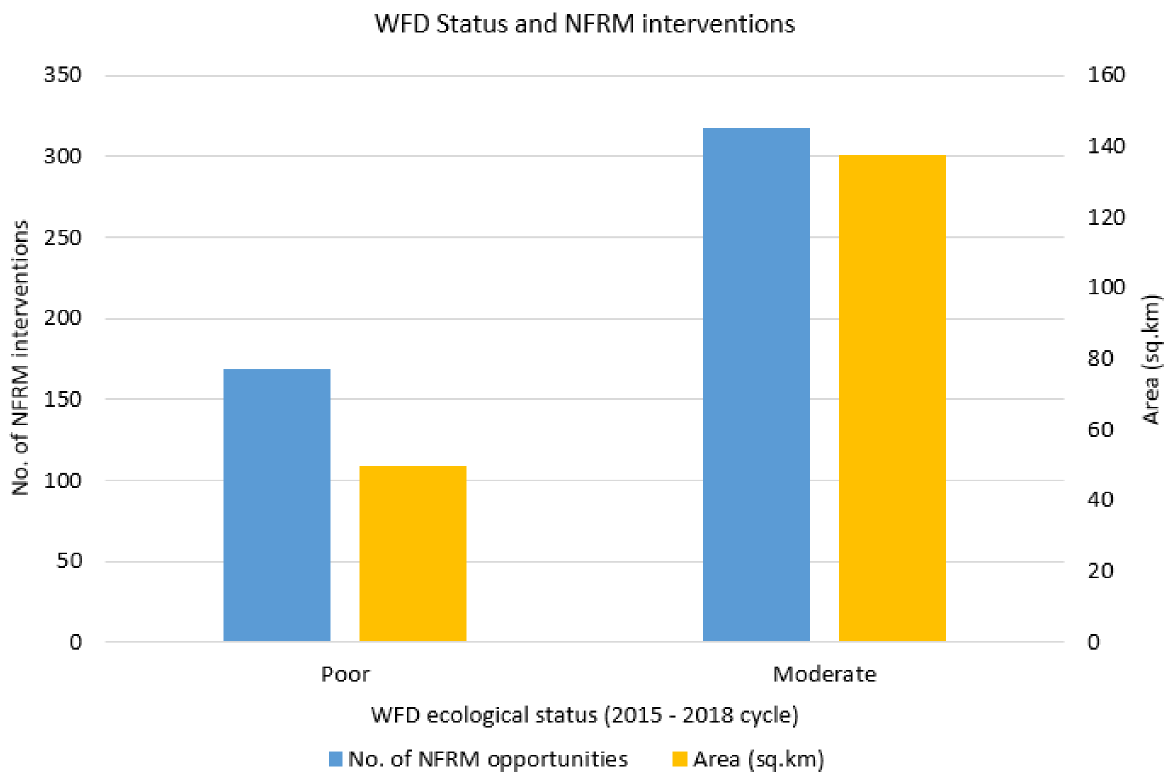


Figure 5.10 Relationship between WFD ecological status and NFRM opportunities

Figure 5.10 demonstrates that 149 (+30.59%) more NFRM opportunities were co-designed in catchments designated as having a 'moderate' ecological status, in comparison to 'poor' ecological status (two of the three dominant sub-catchment across the study site are of 'moderate' ecological status). Whilst this relationship between NFRM opportunities and ecological status indicates a positive relationship between water quality and willingness of farmers/landowners to undertake environmental betterment in the agricultural environment. Based on catchment coverage, 46% of the study site is designated as having 'poor' ecological status and 64% designated as 'moderate'. Further details of the catchments WFD characteristics are provided in section 3.3.

5.3.3 Social Factors

This section analyses the relationship between social factors and NFRM opportunities, with these results presented in Figure 5.11 to Figure 5.14. The relationships indicate pertinent factors that have influenced the uptake of NFRM opportunities, and which could assist other NFRM schemes in prioritising engagement and delivery where it is most adoptable based on desk-based and participant social characteristics. Participant typology proved the most influential factor to NFRM uptake at the catchment scale, followed by agri-environment schemes and lastly land-use class.

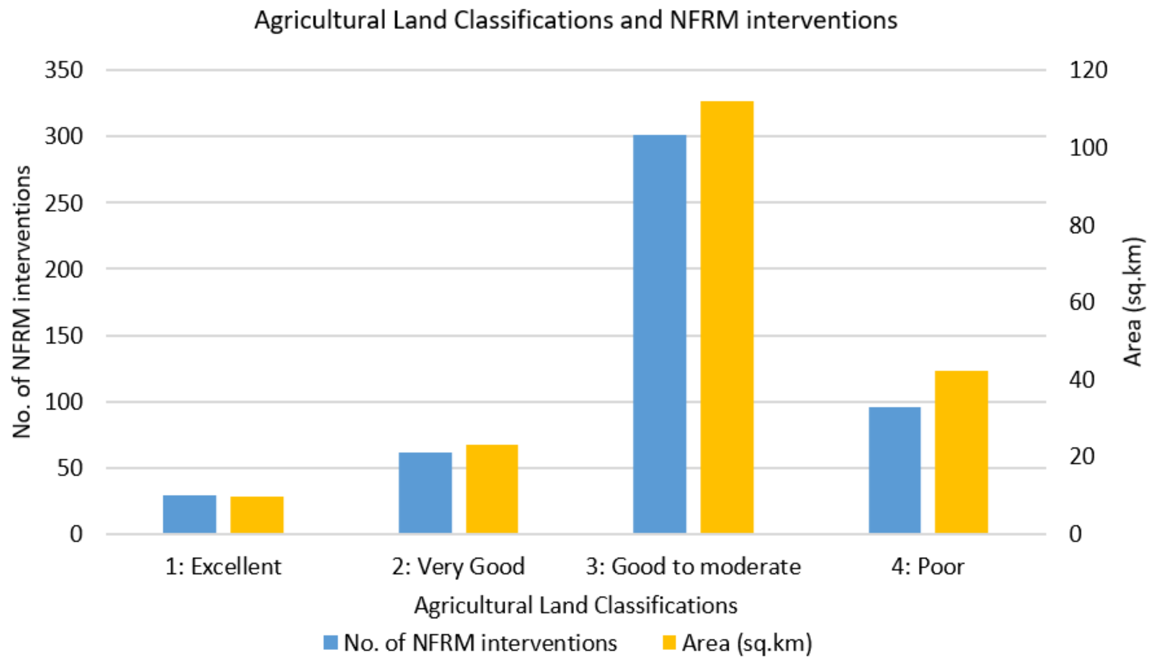


Figure 5.11 Relationship between Agricultural Land Classifications and NFRM opportunities

Figure 5.11 outlines the 60.16% of NFRM opportunities were co-designed in areas of good to moderate agricultural land classification (ALC) (Grade 3). This classification was also the largest in terms of catchment coverage across the study site (57.18%). Only 20.12% of NFRM opportunities were identified in areas of 'very good' and 'excellent' ALC status, which have a catchment coverage of 23.68%. Areas of 'poor' ALC accounted for 9% of the total catchment area, particularly in lowlands and floodplains, and 19.71% of all NFRM opportunities across the study site were situated in these area of low grade farmland. Therefore, Figure 5.11 indicates the lower the ALC the greater number of NFRM opportunities. Further details of the catchments ALC characteristics are provided in section 3.3.

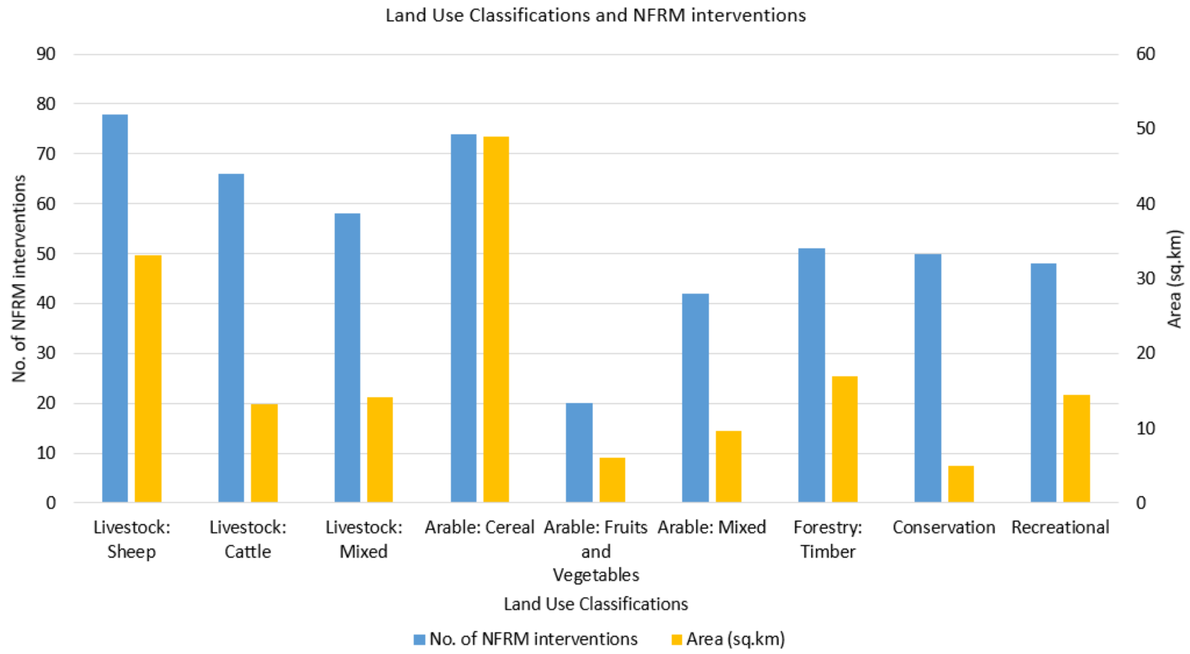


Figure 5.12 Relationship between Land Use Classifications and NFRM opportunities

Figure 5.12 indicates that the majority (16.01%) of NFRM opportunities were co-designed in areas of sheep livestock farming, which accounts for 31.4% of the total catchment coverage. Arable (cereal) land use accounted for 40.98% of total catchment coverage and the second greatest percentage of NFRM opportunities at 15.19%. The least popular areas for NFRM opportunities were arable (fruits and vegetables), which accounted for only 4.11% of NFRM opportunities and 4.30% of total catchment coverage. This relationship indicates a similar relationship to that identified regarding land *cover* in Figure 5.7, in which grassland cover for pasture farming, accounted for less land cover than arable coverage, has more co-designed NFRM opportunities. Further details of the catchments land use characteristics are provided in section 5.2.

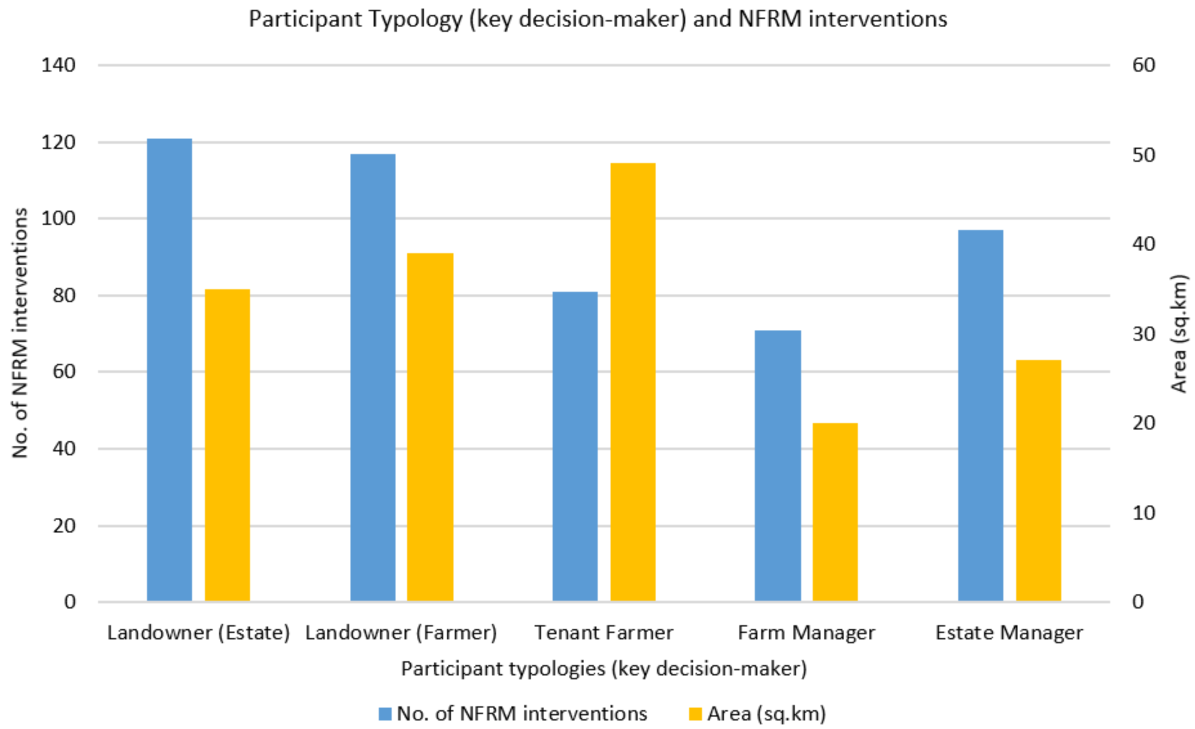


Figure 5.13 Relationship between key participant typologies and NFRM opportunities

Figure 5.13 outlines the majority (83.36%) of NFRM opportunities were co-designed in areas with landowners (those who considered themselves estate owning landowners and farmers who own land), as classified during the PGIS exercises. The landowners acting as the key decision-makers account for 34.19% of the total catchment coverage, with an additional 22.78% of land coverage that is owned (as opposed to tenanted) where the key decision-makers were farm managers and estate managers that accounted for 34.49% of NFRM opportunities. Tenant farmers account for 22.22% of the participants and 22.60% of catchment coverage, but only 16.63% of the total number of NFRM opportunities across the catchment area. This analysis indicates a much greater propensity for NFRM in areas owned as opposed tenanted, with tenant farmers less inclined to co-design NFRM opportunities. Barclay (2010) and Bark *et al.* (2017) also identified tenure as a particular barrier for NFRM uptake, as tenant farmers are especially resistant to altering tried and tested drainage practices that enable a profitable and viable farm businesses. Whilst national government policy for security under tenancies has increased with acts including the Farm Business Tenancy Act (1970) and reviewed in 1995, to provide farmers with security of tenure, many tenants did not participate as actively as landowning farmers and estates. Participant typologies are outlined in section 5.2.

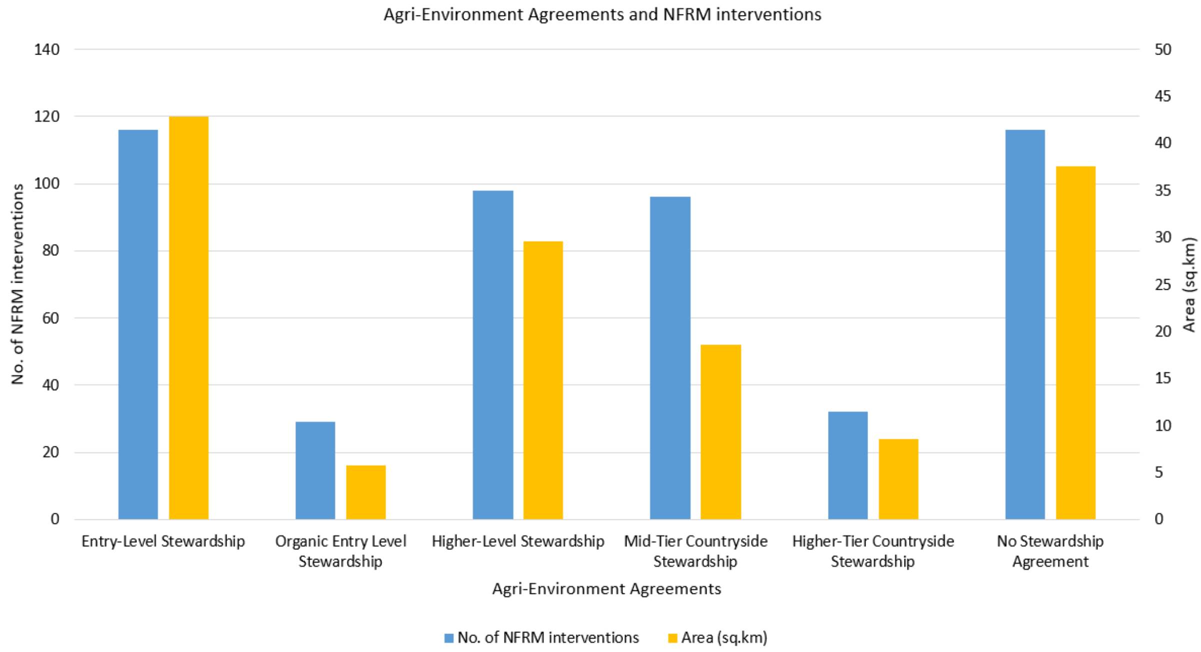


Figure 5.14 Relationship between agri-environment agreements and NFRM opportunities

Figure 5.14 indicates areas under no stewardship agreements to be the most popular (24.02%) for NFRM opportunities, but comprise of 26.32% of total catchment area. The second highest number NFRM opportunities are associated with farms under Entry-Level Stewardship, accounting for 29.51% of the total catchment area where 23.89% of opportunities were co-designed. This strong relationship between coverage and number of NFRM opportunities are closely related to agri-environment schemes, in which no correlation between a particular stewardship scheme and NFRM opportunities can be identified. Landowners and farmers were conscious of identifying opportunities that could be considered Permanent Ineligible Features (PIFs) under Pillar I and Pillar II payments, whereby payments for keeping land in 'good agricultural and environmental condition' could be infringed. The conflicting international and national policy agendas regarding farm and water management are well reported by agencies and organisations seeking environmental enhancements in the agricultural environment (RSPB 2014, WWF 2015 and Natural England 2016). Whilst many reforms to the CAP have included "greening" measures applying WwNP principles, including buffer strips and hedgerows, many farmers were unclear of requirements and thus reluctant to identify NFRM opportunities that could be contrary to policy. Further discussion of the policy influence will be provided in section 7.

6 NFRM Performance Modelling

6.1 Introduction

This section explores the impact of the PGIS-NFRM Opportunities outlined in section 5, using a 1D/2D hydraulic model for different flood risk scenarios (return periods) on flood peaks for the Stour Valley, Warwickshire-Avon catchment. The section explores the performance of the co-designed NFRM Opportunities to varying sized designed-events (QMED, 3.3%AEP, 1%AEP and 1%AEP + 35%). The investigation will compare the baseline results ('do-nothing' scenarios) with the NFRM results (designed in sections 4 and 5, and modelled representation of opportunities outlined in section 3.6).

The scenarios also aim to explore the relative sub-catchment timings of peaks as a result of the co-designed NFRM Opportunities, targeting the areas of greatest upstream contribution to the downstream flood peak in Shipston-on-Stour. The assessment of the relative sub-catchment timings of peaks also reflects on the possible risk of peak convergence (also known as peak synchronisation) across the whole catchment area. Consideration of uncertainty and error is also given in section 6.5 in relation to modelled confidence, to ensure the evidence can be fully understood.

6.2 NFRM Performance Scenarios

This section describes the flood risk (return periods) scenarios to be modelled, the rainfall totals of the input hydrograph and the way in which the scenarios will be tested. Table 6.1 provides an overview of the return periods for NFRM scenarios investigated. These scenarios have been designed to assess the Stour Valley's portioning of NFRM performance based on two factors: (1) as local network results of localised performance of NFRM opportunities within sub-catchments, and (2) at the whole (large) catchment scale, upscaling the performance of NFRM opportunities. This aims to meet the third research aim of potentially identifying the most contributing upstream delineation and, as a result, the most operative PGIS-NFRM opportunities. Each storm will compare a 'baseline' do nothing scenario were NFRM has not been applied, with the co-designed PGIS-NFRM scenario.

Table 6.1 Overview of design storms and rainfall scenarios tested

Rainfall	Comment
QMED – Annual Index Flood	This event is calculated from the median of the set of annual maximum (AMAX) flood data (Kjeldsen 2007), with a return period of once in every two years (50%AEP). The rainfall total across a 12-hr storm duration is 29.54mm (calculated in section 3.6.3). This design event is simulated to a baseline (do-nothing) and NFRM catchment scenarios.
3.3%AEP – 1 in 30 year flood	This event is calculated from the FEH catchment descriptors and volume 2 rainfall frequency estimation method (outlined in section 3.6.3). It has a return period of once in every thirty years (3.3%AEP). The rainfall total across a 12-hr storm duration is 63.42mm (section 3.6.3). This design event is simulated to a baseline (do-nothing) and NFRM catchment scenarios.
1%AEP – 1 in 100 year flood	This event is calculated from the FEH catchment descriptors and volume 2 rainfall frequency estimation method (outlined in section 3.6.3). It has a return period of once in every 100 years (1%AEP). The rainfall total across a 12-hr storm duration is 101.73mm (section 3.6.3). This design event is simulated to a baseline (do-nothing) and NFRM catchment scenarios.
1%AEP + 35% – 1 in 100 year flood plus the climate change allowance	This event is calculated from the FEH catchment descriptors and volume 2 rainfall frequency estimation method (outlined in section 3.6.3), in addition to the Environment Agency Climate Change Allowance (EA 2019c). It has a return period of once in every 100 years (1%AEP), incorporating the *higher central* (+35%) allowance for increase in peak river for the Severn River Basin District (SRBD). The rainfall total across a 12-hr storm duration is 137.30mm (section 3.6.3). This design event is simulated to a baseline (do-nothing) and NFRM catchment scenarios.

6.3 Stour Valley, Warwickshire-Avon NFRM Performance Modelling Results

This section presents the performance of the co-designed PGIS-NFRM scenario to the multiple designed storms in three ways:

1. Flood hydrographs at separate modelled domains and hydrological extents including the Knee Brook (81.8km^2), River Stour (ordinary watercourse reach, including Sutton Brook contribution – 61.2km^2), Nethercote Brook (37.1km^2), Sutton Brook (including Hen Brook – 16km^2), Pig Brook (7.9km^2) and total catchment area in Shipston-on-Stour (187km^2). The modelled domains of each sub-catchment are represented in Figure 6.1.
2. Further analysis of the percentage change in flood peaks (Qp) as result of the co-designed NFRM opportunities in each modelled domain (outlined above), to reflect the performance of NFRM in relation to peak attenuation.
3. Further analysis of the alteration in time to peak (Δ Tp) as a consequence of the co-designed NFRM opportunities in each modelled domain (outlined above), to reflect the performance of NFRM in relation to flood wave propagation lag-times. The latter two hydrograph components are deconstructed and presented in section 6.3.5.

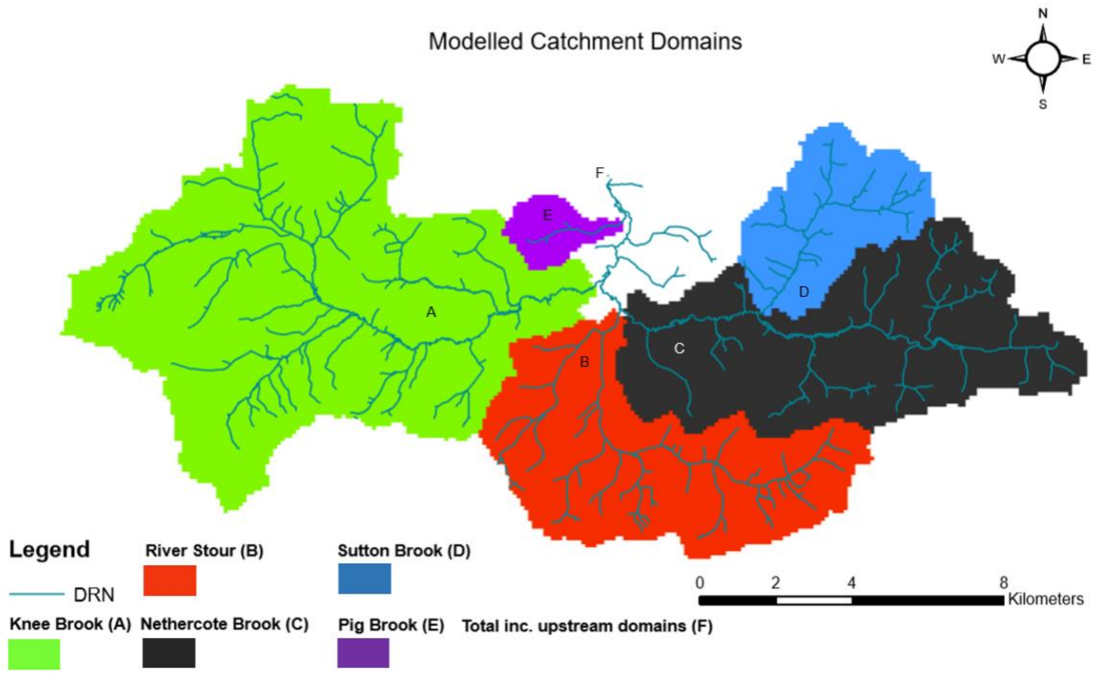


Figure 6.1 Modelled domains across the Stour Valley. Each hydrograph in sections 6.3.1 - 6.3.5 represents the further downstream extent of each of these domains, including the total Stour Valley

6.3.1 QMED: Baseline and NFRM Scenarios

This section presents the hydrograph outputs across all modelled domains (see Figure 6.1).

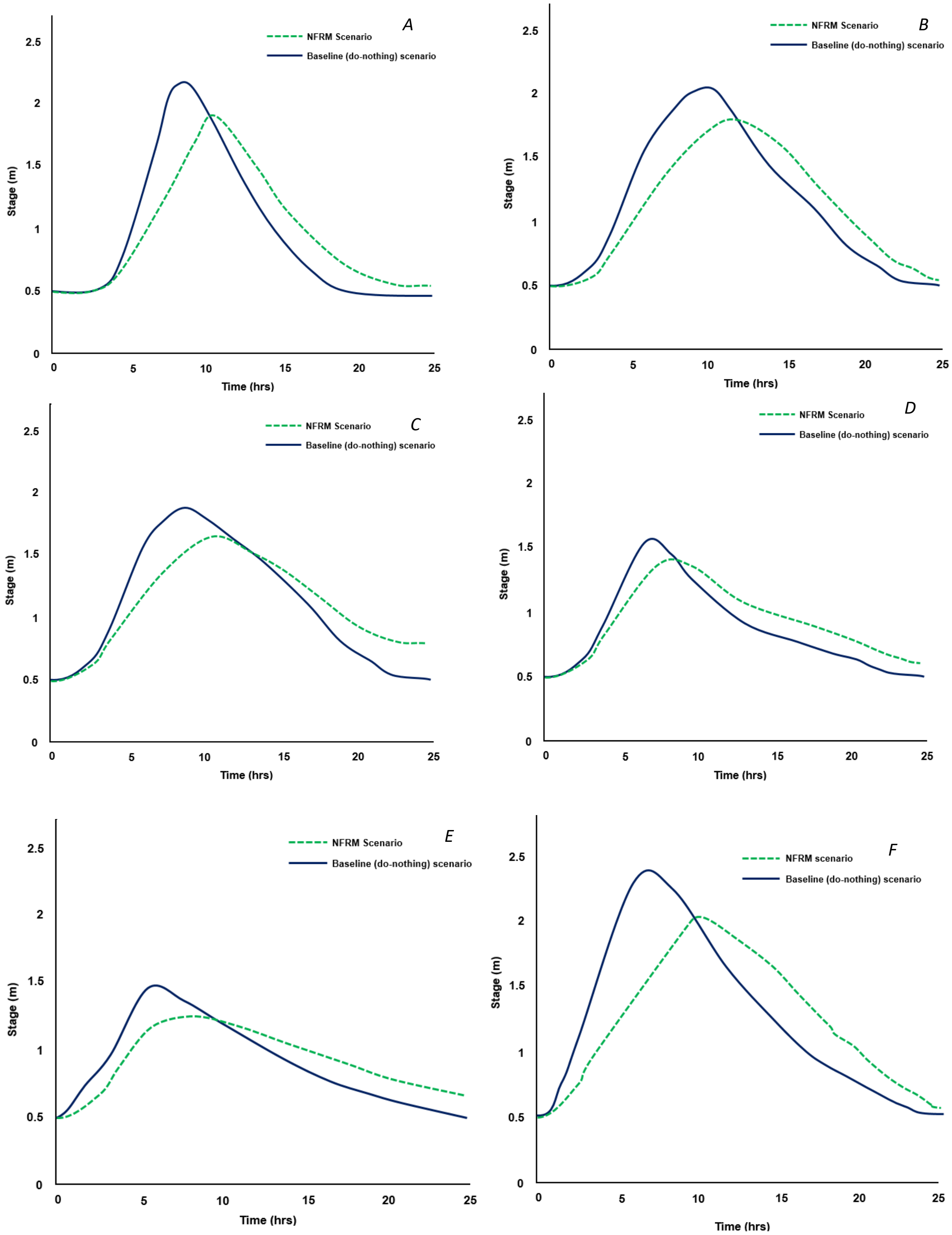


Figure 6.2 Pre and Post NFRM modelled scenarios to the QMED event. A) Knee Brook, B) River Stour, C) Nethercote Brook, D) Sutton Brook, E) Pig Brook and, F) Total upstream catchment area

6.3.2 3.3%AEP: Baseline and NFRM Scenarios

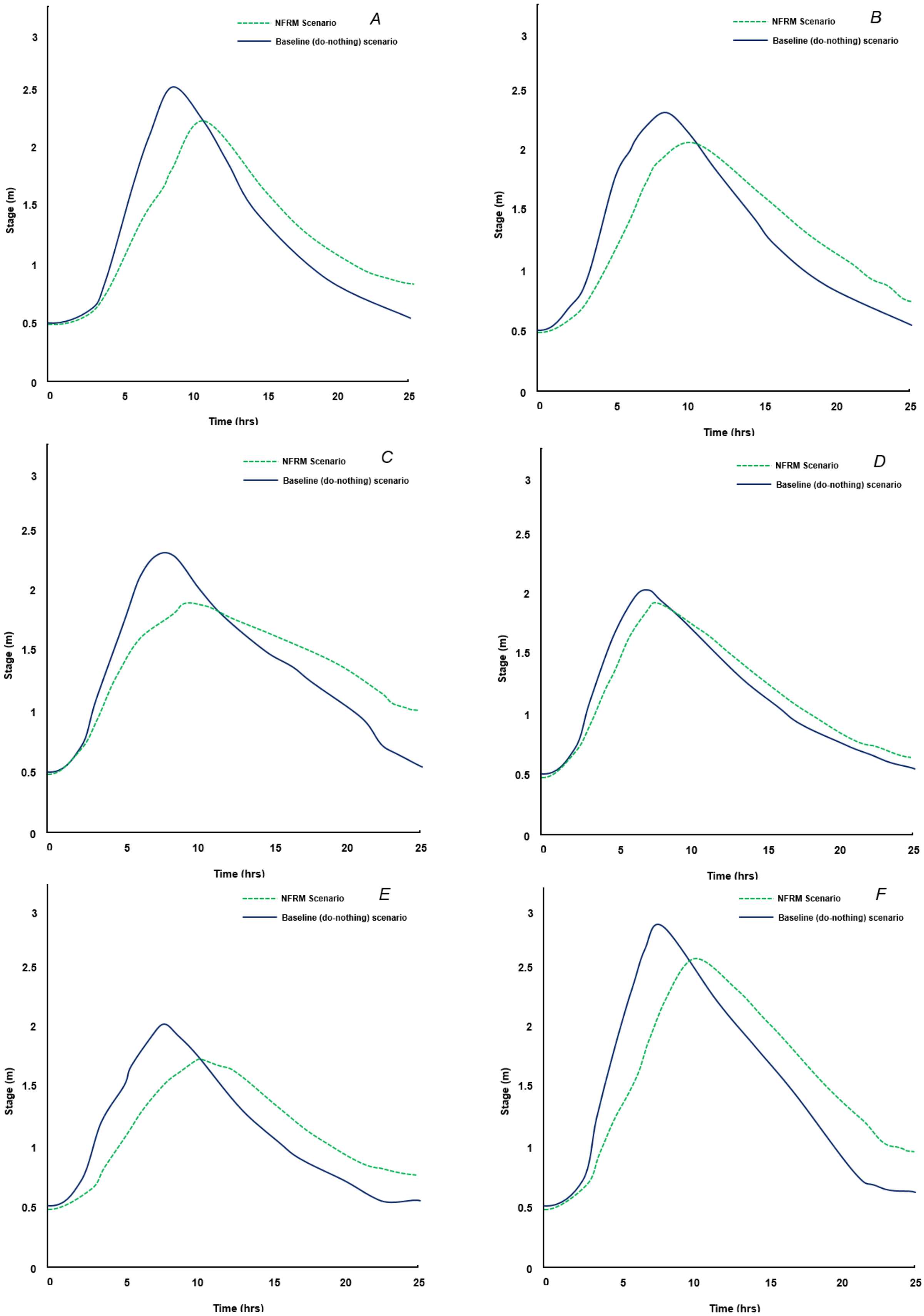


Figure 6.3 Pre and Post NFRM modelled scenarios to the 3.3%AEP event (scenarios same as previous)

6.3.3 1%AEP: Baseline and NFRM Scenarios

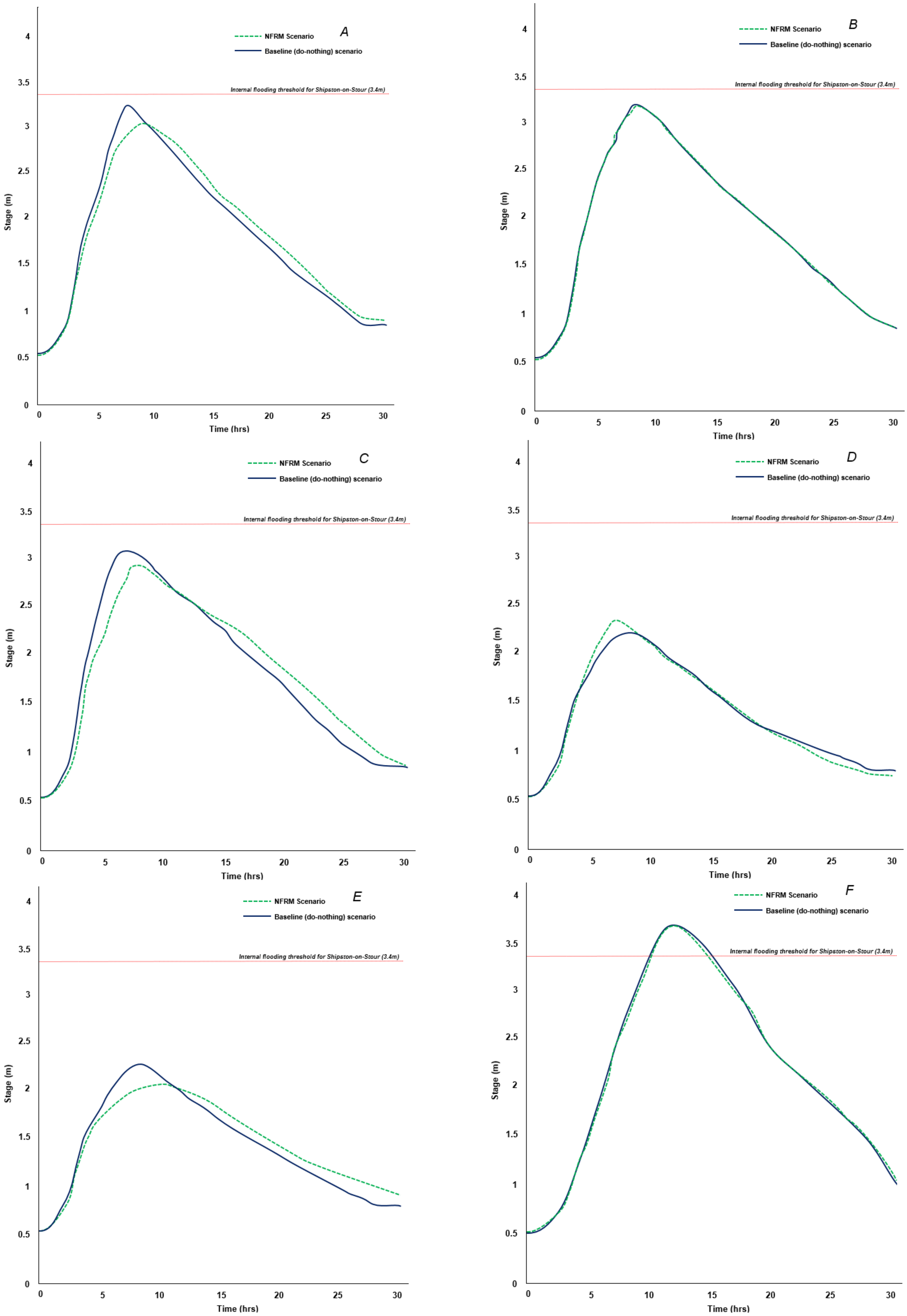


Figure 6.4 Pre and Post NFRM modelled scenarios to the 1%AEP event (scenarios same as previous)

6.3.4 1%AEP + Climate Change Allowance: Baseline and NFRM Scenarios

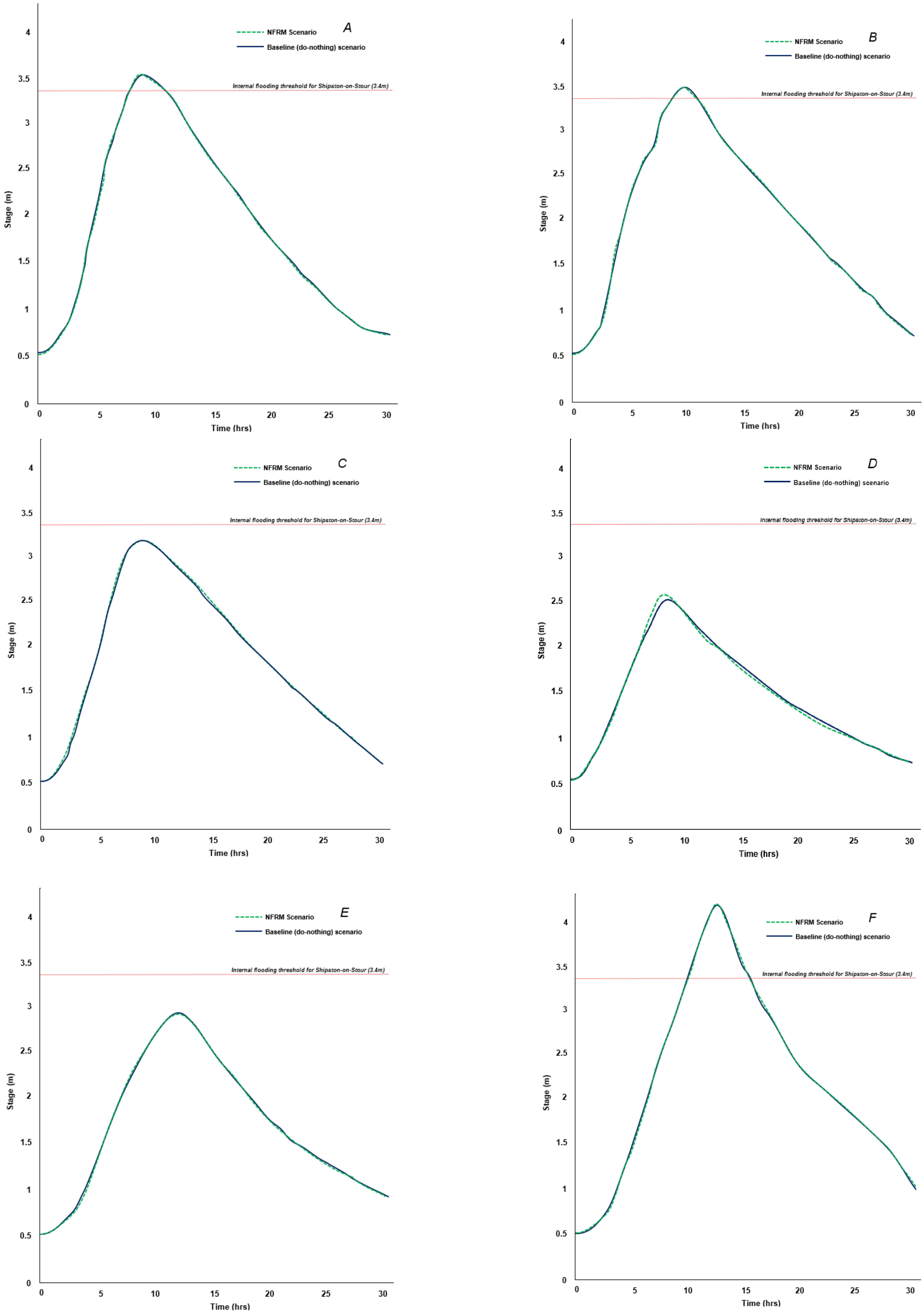


Figure 6.5 Pre and Post NFRM modelled scenarios to the 1%AEP + Climate Change Allowance event (scenarios same as previous)

6.3.5 NFRM Performance Summary: Lag-times and Peak Attenuation

This section presents the deconstructed hydrograph components, synthesising the results presented in sections 6.3.1 – 6.3.4. Table 6.2 provides a summary of the representation techniques for further analysis of results across modelled domains. This results summary section synthesises the hydrograph responses as a result of the co-designed NFRM opportunities in more detail based on percentage change in Qp and difference in lag-times (time-to-peak), critical factors when assessing the performance of NFRM at the catchment scale (Hankin *et al.* 2016a, Burgess-Gamble *et al.* 2018).

Table 6.2 Representation of modelled domains for results further analysis (section 6.3.5)

% AEPs	**Modelled domains**					
	Knee Brook (A)	River Stour (B)	Nethercote (C)	Sutton (D)	Pig Brook (E)	Total (F)
QMED	■	●	▲	▶	◀	▼
3.3	■	●	▲	▶	◀	▼
1	■	●	▲	▶	◀	▼
1 + CCA	■	●	▲	▶	◀	▼

The performance of NFRM was considered highly variable across the catchment's hydrological scales and different storm events the schemes were tested. Figure 6.6 identifies a general pattern that flood peaks were less altered by larger return periods (1%AEP and 1%AEP + CCA) in comparison to smaller return periods (QMED and 3.3%AEP). Exceptions to this pattern were identified in the 1%AEP and 1% AEP + CCA design events in the Sutton Brook (modelled domain D), in which both hydrographs indicated a larger Qp. The 1%AEP and 1%AEP + CCA NFRM scenarios demonstrated a + 0.24m and + 0.32m respectively. This gain in the downstream peak has been attributed to the relative sub-catchment timings of peaks across the Sutton Brook headwater tributaries. Figure 6.7, provides an overview of these tributary peak timings, suggesting the larger designed storms led to peak convergence across the Sutton Brook modelled domain as a result of the NFRM scenarios.

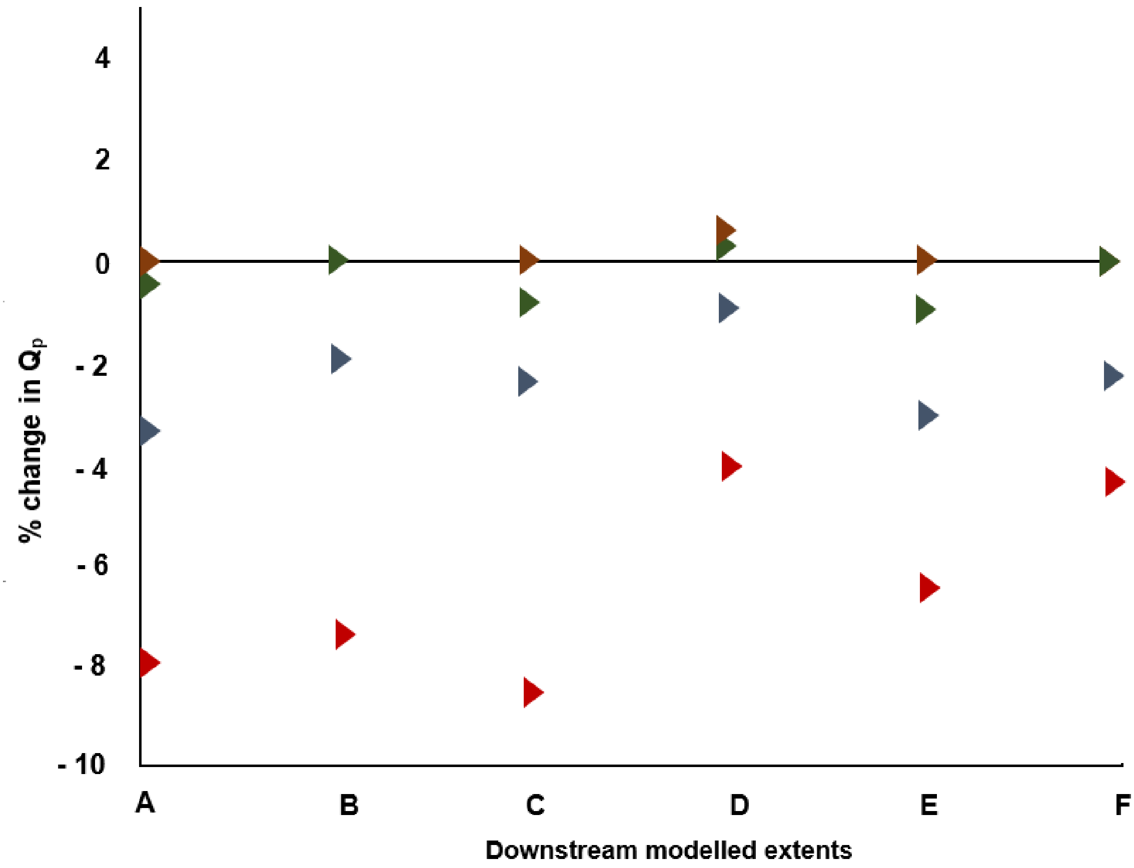


Figure 6.6 Downstream changes in Qp across the total catchment to different sized events.

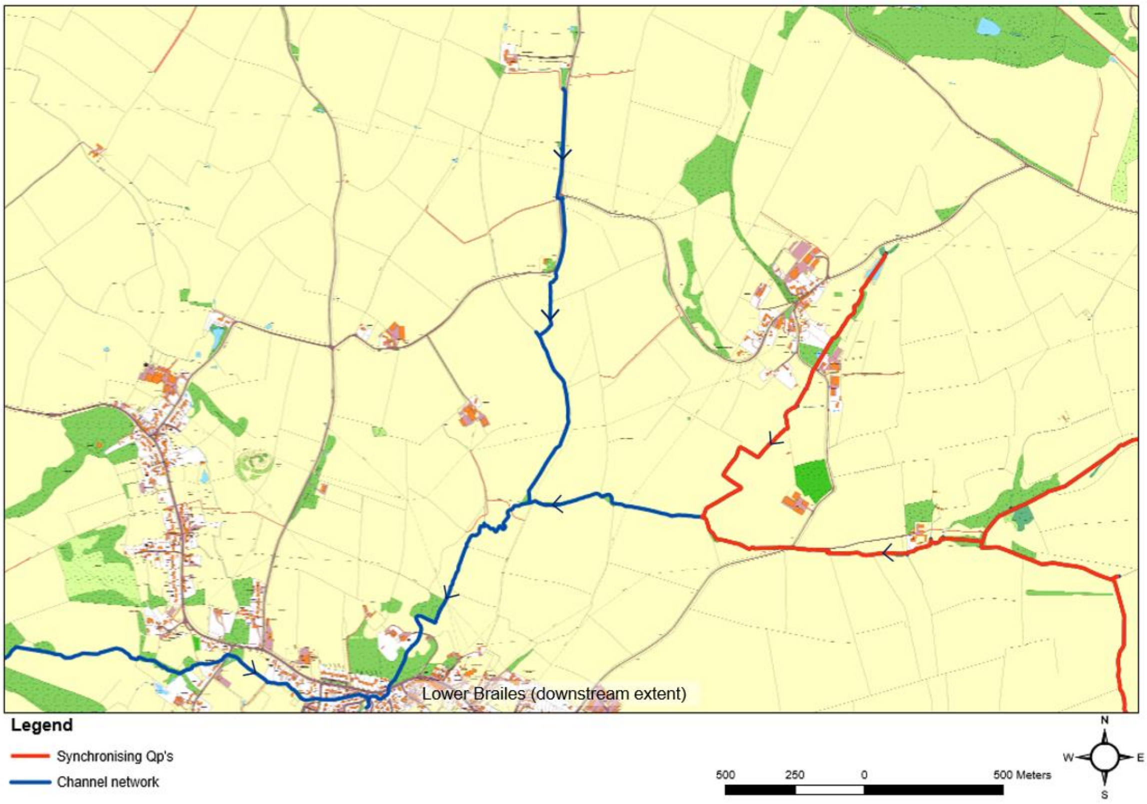


Figure 6.7 Channel network draining into Lower Brailes, including the delineations that synchronised in the NFRM 1% AEP and 1% AEP + Climate Change Allowance that led to a greater downstream Qp response in Lower Brailes (delineation D).

In regards to the smaller flood events (QMED and 3.3%AEP), it is evident NFRM reduced the flood peak at all hydrological scales (localised and large) and across multiple delineations (A – F, see Figure 6.6). The greatest change in Qp as a result of NFRM was identified across Nethercote Brook (C, see Figure 6.6), with an 8.9% reduction in the Qp as a result of the co-designed NFRM scenario to the index flood. This significantly reduced with increasing storm size, to only a 2.1% change as a result of the NFRM opportunities at the 3.3%AEP storm. Figure 6.8 indicates the greatest modification in Tp as a result of the co-designed NFRM opportunities was across Nethercote Brook, supporting Figure 6.39c hydrograph of Nethercote Brooks peak attenuation post NFRM. A general pattern across the catchment was that the larger the catchment scale, the greater the hydrological dilution effects. Figures 6.6 and 6.8 indicates F (the total catchment area at Shipston-on-Stour) as having the most negligible change in Qp as a result of the NFRM scenario: 4% at the QMED design event - 0% to the 1%AEP and 1%AEP + CCA.

The systematic review of case-studies conducted in section 2.5 also identified negligible effects applied at large (>100km^2) catchment scales, with many reviews (e.g. Ngai *et al.* 2019 and Dadson *et al.* 2017) reflecting on the need for more studies in the effects at these sorts of scales. Meire *et al*. (2014) refers to this hydrological dilution as the phenomena in which the other contributing hydrological regimes (including areas without NFRM) dilute the effects of any upstream interventions altering the Qp.

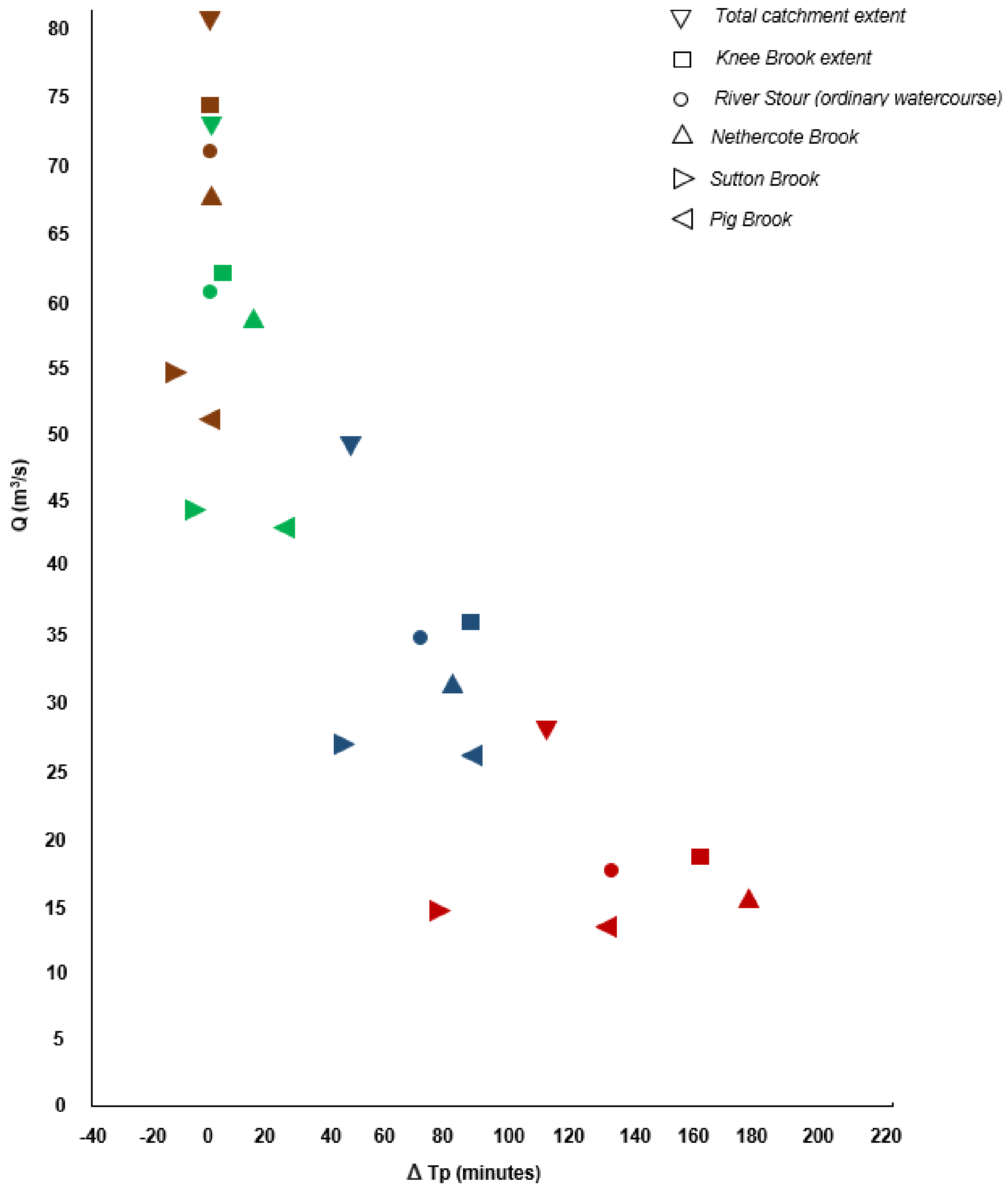


Figure 6.8 Change (Δ) in time-to-peak (Tp) across catchment modelled domains at varying hydrological scales. Colours relate to storm size, Table 6.2 (QMED – 1%AEP + Climate Change Allowance).

The following chapter discusses the results in relation to wider flood risk and NFRM literature, with particular reference to participation in NFRM decision-making (reflecting chapters 4 and 5) and the performance of the co-design NFRM scenario to multiple return periods (reflecting chapter 5).

7 Discussion

7.1 Introduction

This section reviews and discusses the research undertaken according to the objectives and results in meeting aims 2 – 3 (chapter 1.2). Objectives 2.1 and 2.4 (section 1.2.2) were to identify and co-design NFRM opportunities across the total catchment area using a Participatory GIS (PGIS) framework. Objectives 3.1 and 3.5 (section 1.2.3) were to assess the performance of the co-designed PGIS-NFRM schemes to multiple storm events at varying hydrological scales. Furthermore, this section will review the overall value of the co-design framework in relation to NFRM performance modelling, and the research's contribution to knowledge in the fields of NFRM engagement, performance and policy at the local and international scales.

7.2 Aim 2 – Participatory GIS NFRM Opportunity Mapping

This section discusses the results of the PGIS-NFRM exercises across the study site summarised in section 5, which highlighted the large variation in levels of participation between landowners and tenants farmers to co-design NFRM opportunities. The Pilot Farm Study (section 4) provided an example of how a landowner was able to contribute valuable local knowledge of overland flow routes, historic changes in land management (such as ditching and drainage practices), and historic flood events that caused flooding to downstream properties and businesses, as well as issues to their land management, including soil loss, degradation of crops and impact on livestock. Section 4 also included lessons learnt in order to upscale the PGIS framework to the large catchment scale (187km^2). This section seeks to explore the effectiveness of the PGIS framework in more detail, in not only identifying *problems* of hydrological connectivity (section 3.4.2), but also using that information to co-design NFRM opportunities across the study site to devise place-based *solutions* (section 3.4.3). Cadastral land use patterns of participants and local, national and international drainage, flooding and agricultural land management policies will also be discussed in relation to the NFRM opportunities (Rouillard *et al.* 2015, Waylean *et al.* 2018, Benson *et al.* 2016 and Dworak and Gorlack 2005).

7.2.1 Level of Engagement in PGIS NFRM Opportunity Mapping

Despite the alternative approaches of most NFRM studies that have focused on initially modelling a possible scheme before engaging landowners and farmers in the opportunities and possible uptake (outlined in section 3.5), this study sought local involvement in NFRM decision-making from these critical stakeholders (Short *et al.* 2016, Waylean *et al.* 2017). The primary emphasis on modelling of largely invalidated NFRM opportunities is unhelpful to farmers and landowners, for whom flood risk and drainage is one of a myriad of farming and land management considerations (NFU 2016). The methods used by previous NFRM feasibility assessments, including remote mapping and modelling studies, e.g. SEPA (2016), JBA (2018), Halcrow Group (2008) and Nicholson *et al.* (2012) have considered engagement as a follow up activity, to passively engage (Lane *et al.* 2015) farmers and landowners to *inform* them of the opportunities, instead of *actively* engage (Leadoux *et al.* 2003) in order to obtain local knowledge and indicate what is adoptable for the landowners and farmers.

Few studies have co-designed and mapped NFRM opportunities, particularly across a large catchment area. At this scale, prior scoping studies, e.g. Broadmeadow *et al.* (2010), SEPA *et al.* (2016) and JBA (2018) have used entirely remote desk-based spatial datasets to identify NFRM opportunities, with a restricted number of influential factors including areas of high flow accumulation, hydrological connectivity, fluvial flood extents, propensity for infiltration, and any constraints and sensitivities. These datasets have similarly been considered within this study as part of the desk-based characterisation used to create the Farm Information Packs (FIPs) (meeting aim 1, Appendix D). As recommended by other local engagement practices in flood risk and wider environmental management, e.g. the Integrated Local Delivery Framework (Dale-Harris and Phelps 2017) and the Stroud Rural SuDS Project (Short *et al.* 2016 and Uttley 2015), this study used local gatekeepers in the form of Natural England, the National Farmers Union and a local flood action group of residents. The use of gatekeepers enabled the study to obtain a 100% coverage of the total catchment areas' farmers and landowners, through trusted intermediaries between the researcher and research participant. 26% of these farms and estates were also outside of the Rural Payments Agency's boundaries data.

Although there was a large coverage of the PGIS exercises across the catchment (conducted to meet aim 2), the level of engagement in co-designing NFRM opportunities was highly variable. As outlined in section 5.4.3, landowning participants co-designed the greatest percentage of NFRM opportunities (83.36%), with more by those who considered themselves estate owning landowners as opposed to farmers who own land, as classified during the PGIS exercises. Proportionally, these landowners acting as the key decision-makers accounted for 34.19%, representing a much greater likelihood for NFRM adoption by landowning participants as opposed to tenanted farmers. The Tweed Forum (2017) also found this to be the case when attempting to restore floodplain and cross-slope native woodland to alleviate downstream flooding in Crookston Farm, Selkirkshire. The tenant farmer was heavily motivated by the financial returns of the scheme, linking the NFRM opportunities to potential stewardship (under the Flood Risk Management (Scotland) Act 2009), as opposed to flood risk reduction benefits. Wingfield *et al.* (2019) refers to the need for research and scoping strategies to go beyond the flood risk evidence debate in order to deliver multiple benefit FRM schemes, including NFRM. Furthermore considering multiple ecosystem services that could incentives farmers and landowners to adopt WwNP techniques, including stewardship for wider land management changes seemingly outside of flood risk, e.g. habitat provision.

This PGIS research framework has differed to the view that farmers are more engaged by other ecosystem services compared to in local FRM (Batary *et al.* 2015). The scope of the NFRM opportunities were entirely based on intercepting sources and pathways of flood flows that could contribute towards downstream flood risk. However, considerable onus during the scope of opportunities was placed on the location of existing stewardship arrangements in relation to potential NFRM opportunities across tenant and landowning participants. Environmental stewardship as designated under the CAP (1963) agri-environment schemes encourage farming practices that enrich and safeguard declining biodiversity (Batáry *et al*. 2015, Boatman *et al*. 2008). Countryside Stewardship was the latest agri-environment scheme introduced in the UK in 2016, and within the scheme there is provision for some NFRM interventions (Natural England 2017).

The inclusion of NFRM however is based upon a targeted system of funding as set by Natural England, primarily based on capital grant items of tree planting in various locations (Riley *et al*. 2018). This has led to FRM agencies and partners overlooking the role of agri-environment schemes to deliver NFRM. In updated Flood Risk Management Plans (FRMPs) (Environment Agency 2016d), only 14% national FRMPs clearly references Countryside Stewardship, with most acknowledging the need for greater involvement from the farming sector. Yet conversely, two FRMPs do not link flood risk and agriculture of any kind (Environment Agency 2016d). The siloes of land use management concerns were also found to be the case in the Stour Valley, with farmers and landowners avoiding the identification of NFRM opportunities in areas of stewardship, e.g. margins and habitat areas (outlined in section 5.4.3). Therefore, the continued disaggregation of farming and flood risk in policy objectives proved a constraint for the wider identification of NFRM opportunities.

A method of adoption that could reflect such an integrated policy approach can be found in continental Europe in the Integrated Water Resource Management (IWRM) transition (Calder 2005). Responding to mounting evidence of ecological degradation in freshwater environments and social effects on livelihoods, codes were established for a 'harmonised approach' that manages water and land in one holistic system, ensuring sustainable and equitable management. In EU policy, IWRM adopted legislation from the Water Framework Directive (WFD) (2000) and RBMPs (Richter *et al*. 2013, Kundzewicz and Menzel 2005, Rahaman *et al.* 2013); seconded by the EU Floods Directive (2007). The motives of these international policies was to encourage "synergies" through integrated targets and enabled directive delivery (Neuhold 2014) aligning these targets in wider RBMPs and FRMPs, which use the same hydrological extents and share six year management planning cycles (the latest of which updated by Environment Agency 2015). The integration of water management authorities in FRM through the synergies of FD and WFD provides the prospect of NFRM promotion that delivers ecocystem-services (Collentine and Futter 2016), nonetheless the practical assimilation of both international policy directives are not subject to a UK review.

Participants that focused on existing stewardship to avoid the co-design of possible Permanent Ineligible Features (PIFs) did not clarify which other NFRM opportunities could be targeted in future stewardship. To pre-empt this point, the NFRM guidance document (Appendix C) illustrated the full range of NFRM options, including those linked to Countryside Stewardship. Inclusion of several NFRM opportunities within distinct themes (Runoff Management, River and Floodplain Management and Woodland Management) also conveys to participants that alternative NFRM opportunities are available if a particular NFRM technique is undesirable in specific environments. Utilising the method of communicating all options through a consistent presentation of techniques with the rules applied in this research could support improved understanding amongst NFRM researchers and practitioners of the range of available NFRM opportunities. The method and results also plays a role in addressing the absence of guidance for researchers and practitioners in understanding suitable NFRM techniques for different catchment characteristics (Holstead and Kenyon 2017, Duffy *et al.* 2016, Avery 2012). However, unlike the Scottish Rural SuDS Guidance (Duffy *et al.* 2016), this is not aimed to be a 'design and build' technical document, but rather a guiding document with assistance from a facilitator.

7.2.2 Using local knowledge to identify sources and pathways of flood risk

The essential component of the PGIS maps conducted to meet the second aim (results provided in section 5) was the local knowledge provided to refine the desk-based analysis conducted within the first aim (objectives 1.1 – 1.4). The local knowledge was used to validate the analysis of the farms hydrological connectivity, flow pathways and underlying characteristics provided in the FIPs (example in Appendix D) from the desk-based characterisation. Whilst local knowledge largely complimented the FIP maps, 63% of the participants provided conflicting information of flow routes and areas of hydrological connectivity indicated by RoFSW, RoFR&S and SCIMAP. This is not to assume the data is erroneous or the method to identify those flow pathways or flood extent are incorrect, but local knowledge refined the GIS open data sources to improve the place based understanding of the farms' hydrological response. In practice, participant contributions of local knowledge were the preferred basis when identifying sources and pathways of flood risk. McEwen and Holmes (2017) refer to the disproportionate weight of ‘flood memories’ in local FRM decision-making, in which remote data sources including modelled extents are considered less valid than observations made by key local stakeholders. In the case of the Stour Valley, this process can be referred as ‘flood archiving’ (Hansen *et al.* 2016, McEwen and Holmes 2017), in which farmers and landowners relied on their own understanding of the hydrological response to rainfall events.

Figure 7.1 provides an example of the raw PGIS data mapped during the PGIS-exercise, where a farmers annotated flow route differed with the RoFSW layer, and identified another flow pathway that was believed to be more active in heavy rainfall events. Reference years were used to provide details of varying flood extents, depths and times the land was inundated. This information is commonly gathered through a modelling exercise, however, by obtaining local knowledge early, it provided a spatial insight into the flood risk sources and pathways across the catchment-scale.

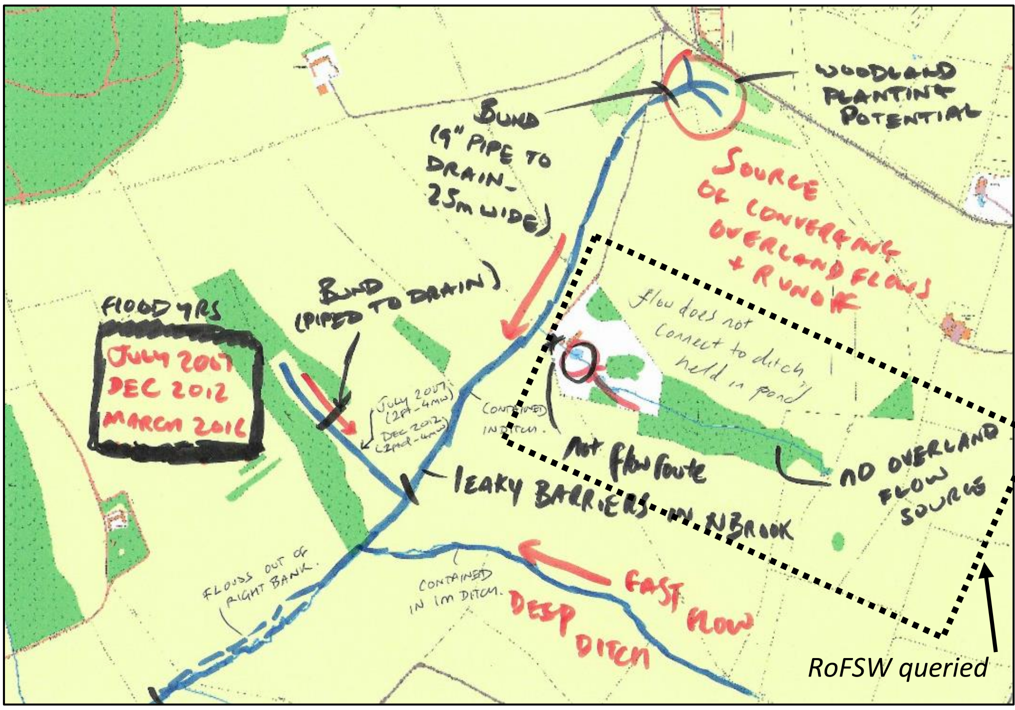


Figure 7.1 Raw PGIS map in Nethercote Brook, queried RoFSW layer by farmer

The use of local stakeholders to undertake ‘flood hazard mapping’ has been well reported and discussed in section 2.3.1. However, this is commonly applied by residents directly affected by flooding, who collaborate to improve their collective understanding of upstream hydrological processes that could enhance downstream flood risk (Priest and Pardoe 2012). An example of such an exercise that used downstream residents was conducted in Kajang, Malaysia where Muhamad, Lim and Pereira (2016) used terrain maps that residents could confirm flood extents and depths during a particular large event in December 2011.

Across the Stour Valley, many farmers and landowners identified 'new' flow pathways and areas considered to be the source of flood flows, known as critical source areas, that were not identified in the RoFSW or SCIMAP datasets. This enabled farmers and landowners to concentrate NFRM opportunities in areas that caused the greatest problems for downstream flooding, undertaking a risk-based approach to the situating of NFRM at the farm-scale. Furthermore, some farmers and landowners were able to identify problems to the farm business as a result of the PGIS exercise and FIPs, recognising the need to address flow routes that were causing top soil loss and bank erosion. This enabled the 'problems' of flooding to be shared and collectively resolved with the recognition of mutually benefiting from WwNP principles, both devising a solution for downstream flood risk problems whilst reducing effects on the farm business as a result of how the farm responds to heavy rainfall events. Maiden, Jones and Wilson's (2018) review of the RoFSW layers used in local food risk management strategies (LFRMS) (discussed in chapter 3.2) identified a similar benefit of collaborating the dataset with local knowledge, where inaccuracies were identified the incorporation of local knowledge was advocated, but a method to do so not provided. Local knowledge was considered especially important for 'hot spot' identification, areas in which flooding to local infrastructure, properties and businesses could be incorporated to refine the RoFSW layer in LFRMSs. As opposed to just identifying the receptors of flooding, the PGIS framework employed enabled the identification of sources and pathways to address before 'hot spots' become inundated.

The Stroud Frome Rural SuDS scheme employed public participation to foster co-learning and frame local knowledge of the problems and possible NFRM across the catchment (Short *et al.* 2018). The project employed site-based meetings to communicate the problems (verbally) and negotiate any

NFRM opportunities (Baron and Tustig 2005) - encouraging a collaborative effort that is a paradigm shift to traditional FRM (as discussed in chapter 2.3). The FIPs and PGIS maps provides greater transparency and justification of the problems being addressed with the multi-stakeholder processes being recorded through annotated community mapping. Flood memories also enabled some landowners and farmers to reflect on changing land management practices between events that could have altered the hydrological response of their holdings. Figure 7.2 outlines a farmer who identified the flood extents pathways of an event in April 1997 that connected to the receiving watercourse, whilst in subsequent events (with the exception of July 2007) a series of existing ponds (implemented in 2005) were able to intercept and store the flood flows, before slowly draining after the heavy rainfall events. Garde-Hansen *et al.* (2016) refer to these 'memory practices' as critical tools to engaging and informing LFRM planning, from qualitatively monitoring performance of a scheme, to building local resilience and knowledge of flooding patterns. However, the use of these recorded memories in visual detail has not previously been applied to NFRM and enables integration of local knowledge transparently into NFRM scoping studies.

The site based investigations into which sources and pathways have the greatest potential impact to downstream flooding through PGIS showed that each farm and landowner had different experiences of events based on a host of reasons, including changing land management, size of the event tested and more difficult to determine: the reliability of the memories. During the PGIS exercises participants were encouraged to only include information on flood characteristics they were confident had occurred (as discussed in Chapter 3.4). Merz *et al.* (2007), Brown *et al.* (2002), Landstrom *et al.* (2011) and Hall *et al.* (2003) conceived that whilst local knowledge is highly valuable when encouraging integrated and sustainable FRM, scrutiny and often 'expert judgement' is required to determine the validity of those inputs. The requisite for 'expert judgement' inhibits the ability to actively engage, in the case of farmers and landowners, ensuring a hierarchy of knowledge is sustained and prevents further sustained engagement and collaboration. The PGIS results identified the heterogeneous nature of local knowledge, with some farmers and landowners identifying more precise indications of referenced flood extents and depths than others. Therefore, the data gathered and projected in the catchment characterisation (objectives 1.1 to 1.4) provided a baseline of technical understanding provided at the outset, which participants could refer to and scrutinise along with their own understanding of their farms and estates flood sources and pathways.

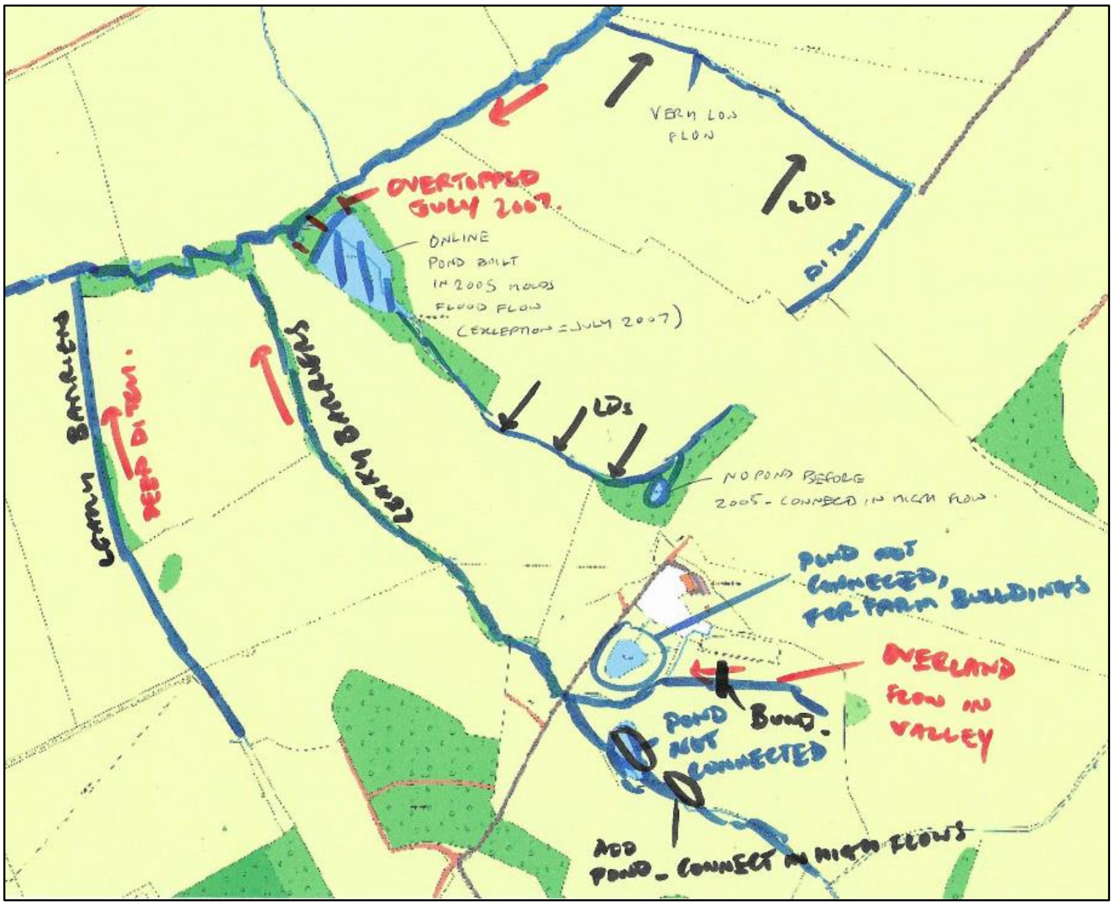


Figure 7.2 Flood memories employed to record effects of ponds implemented in 2005

7.2.3 Co-designing NFRM Opportunities

This section first discusses the implications of the potential opportunities of NFRM in the Stour Valley in relation to questions surrounding the use of the PGIS framework to co-design NFRM opportunities (section 7.2.3.1). Potential applicability to other catchments is also discussed (section 7.2.3.2), differing to the more traditional flood defence scoping strategies that seek to model opportunities before undertaking any location consultation (Speller 2005). In addition to the mapped examples presented, Lavers and Charlesworth (2018) have used the opportunity maps to outline the potential value of PGIS to co-design NFRM opportunities across large catchments (Appendix G). This research also supplements the NERC funded LAND-WISE project that is exploring the merits and challenges of community engagement and partnership working in NFRM (Mehring *et al.* 2018).

7.2.3.1 Implications of NFRM Opportunities

In addition to urban creep, agricultural land use has a substantial effect on catchment hydrology and river response, and the level of agricultural intensification is a factor studies have considered when assessing changing flood patterns (most notably O'Connell *et al.* 2004 review). With NFRM defined as measures that help to protect, restore and emulate the natural functions of catchments, floodplains, rivers and coasts (Environment Agency 2016a), in the context of this thesis, restoration has been an underpinning principle, seeking to restore a less intense agricultural landscape (predating war-time intensification) (Jones 2010). Consequently, the historic land use compared to current farming practices at the site scale will heavily influence NFRM opportunities, yet few published UK and international studies have considered these factors when situating NFRM, for example the River Ray, Wiltshire, UK (Ormesher 2018) and the River Regge, Netherlands (Muhar 2016). River restoration has been the main technique that have utilised historic maps and LiDAR models to identify historic watercourse lines (discussed from section 2.5). More NFRM studies have assessed land cover instead of land use (e.g. Nisbet *et al.* 2015), classifying areas based on their hydraulic roughness instead of how the land is used, and how those uses compare to historic farming practices and adoptable NFRM opportunities for different land uses.

Section 5.4.3 (Figure 5.15) outlined nine different land use classifications associated with were NFRM opportunities were identified, including: livestock: sheep, livestock: cattle, livestock: mixed, arable: cereal, arable: fruits and vegetables, arable: mixed, forestry: timber, conservation and recreational. Classes were based on MAFF (1998) and conversions from land cover to land use as outlined by Harrison (2006: 15), verified during the PGIS process. The largest percentage (16.01%) of NFRM opportunities were situated in sheep-grazed livestock farms, in which sheep livestock farming accounts for 31.4% of the total catchment coverage. Arable (cereal) land use accounted for 40.98% of total catchment coverage and the second greatest percentage of NFRM opportunities at 15.19%. Therefore, NFRM techniques were considered more adoptable in pasture rather than arable farms. Spray *et al.* (2015) also found this to be the case in the Eddleston Water scheme, with areas of pasture being used for large attenuation areas, enabling them to be multi-functional - both grazed and for flood storage.

7.2.3.2 Applicability of PGIS framework to other catchments

Whilst NFRM scoping methods are recommended to be tailored to the particular catchment (e.g. JBA 2018), the Stour Valley is atypical of other large dendritic uplands with mixed agricultural land use and large levels of private ownership and environmental stewardship agreements. Exclusions to comparisons to other case-studies in the meta-analysis (section 2.5.1) are the social characteristics, including ownership, stewardship and land use; much of this information was gathered for the Stour Valley during the PGIS framework, sourced from participants and not available from other studies.

This study was conducted in a rural setting, additional research into a more urbanised catchment could evaluate the replicability of the approach where the PGIS framework would need to engage different riparian landowners, principally LPAs/LLFAs who manage the ordinary watercourses. In the case of a rural catchment, identification of suitable proxy measures for certain land uses and site specific details might substitute for unavailable data, with advice and recommendations for how to use assisting in the accelerated scoping and potential adoption of NFRM opportunities. If NFRM is to be more widely adopted, as endorsed by the Environment Agency's NFRMS (Environment Agency in press) and EFRA Committee Report (2016) in response to storms Desmond, Eva and Frank, there may need to be a shift in attitude towards how NFRM opportunities are identified, away from being treated as traditional flood defence schemes, each requiring detailed appraisals - and towards a more grounded approach as adopted by this research, allowing for multi-criteria decision making (Nardini and Pavan 2012, Wilkinson *et al.* 2013, Cornell 2006). This could include an array of standard techniques for different catchment characteristics (physical, hydrological and social) that enable farmers and landowners to be more informed about potential opportunities, developing some of the recent guidance in a similar area, e.g. Rural SuDS Design and Build Guidance (Duffy *et al.* 2016), NFM: A Farmers Guide (SRUC 2019) and NFM Measures: A Practical Guide for Farmers (Yorkshire Dales Rivers Trust 2018). However, this impetuous to install NFRM must be weighted with the evidence of how such schemes perform, particularly to ensure any possible scheme does not provide any dis-benefits (Lane *et al.* 2015), discussed further in section 7.3.

7.3 Aim 3 – NFRM Performance Testing

This section discusses the findings from the modelled scenarios presented in section 6. The NFRM opportunities tested are those co-designed using the PGIS framework, and discussed in section 7.2.

7.3.1 Relative sub-catchment timing of peaks

The modelling of the catchment delineations that applied flood impact modelling (FIM) principles (Nicholson 2012) highlighted the significance of assessing how the catchment's component delineations respond to varied storm events. Extensive modelled studies have shown targeting NFRM at different delineations have had varied impacts at the furthest downstream extent, even at large hydrological scales (Blanc *et al.* 2012, Beven *et al.* 2018, Hankin *et al.* 2017, Chappell *et al.* 2017, Reaney and Pearson 2014, Pattison *et al.* 2014). The overall concept of storm flow propagation across large catchments allows for an infinite number of scenarios to be considered, across a variety of NFRM techniques and return periods. This research refined the scenarios tested by undertaking a co-design PGIS process to identify a realistic scope of NFRM opportunities.

Questions about peak synchronisation, and the degree of assessment required to identify and avoid such an outcome is disputed in literature and practice. Hankin *et al.* (2017) adopted a full modelled scope, prior to engagement, in order to identify the converging peaks across the Eden, Derwent and Kent, UK. This was supplemented by an intense hydrological monitoring network of both the rainfall and river flow network. However, ungauged and particularly large (>100km^2) catchments often lack the level of baseline data to inform such detailed hydrological assessments of the catchment's flow characteristics. Such projects, including the Stroud Rural SuDS scheme, relied on obtaining more anecdotal detail from considerable local engagement in order to facilitate an NFRM scheme based on local knowledge (Uttley 2016). However, the latter of the scoping methods often negates any assessment into the relative sub-catchment timings of peaks due to the lack of observed data to assist in building a reliable catchment model. The method used in this study devised a hybrid scope that used available observed data to model the catchment (section 3.6.4), after an earlier PGIS phase (section 3.5).

The modelling results (section 6.3) highlighted that the catchment scale effects of NFRM are more greatly diluted the larger the hydrological extent they are tested. The impact of mitigation was most heavily identified at the small-medium catchment scales, in the sub-catchment extents (most notably Nethercote and Knee Brooks). The tributaries within the relative sub-catchment's timings of peaks were not assessed as part of this thesis, and therefore any de-synchronisation effects cannot be ascertained. However, synchronisation of tributary feeds within Sutton Brook was identified as a dis-benefit of the NFRM scenario to the 1%AEP and 1%AEP + Climate Change Allowance, resulting in a greater downstream Qp in Lower Brailes, Warwickshire. Mass balance checks identified the same volume of water in the hydrograph, however, the converging peaks led to a shorter time-to-peak with a reduced lag-time in the river response as a result of the NFRM scenario (section 6.3.5).

In terms of prioritisation across the catchment-scale, Knee Brook was identified as the delineating sub-catchment with the greatest travel distance, hydrological contribution and flashiest time-to-peak across all return periods tested. Other modelled studies identified risks in slowing proximal sub-catchments to the outlet, with an increased likelihood of convergence (Owen 2016); however, even with a large number of NFRM opportunities co-designed across Pig Brook (the closest sub-catchment to Shipston-on-Stour), convergence of peaks was not identified.

A key caveat with the assessments of the relative sub-catchment timings of peaks within this study is the limited gauged spasmodic rainfall and delineated baseline flow data available to disaggregate the upstream flow regimes within the model. The FEH design storms have limitations in homogenising complex localised flows that will be discussed in section 7.3.3, and require rainfall and gauges to within $10km^2$ to more representatively replicate the possible river responses (Arnott *et al.* 2018).

7.3.2 Peak attenuation and flood mitigation

The investigation into testing the performance of NFRM across the Stour Valley to meet the third aim (objectives 3.1 – 3.5) not only identified key upstream contributions across the multiple return periods (section 7.3.1), but also upscaled the performance of highly dispersed NFRM opportunities to the large catchment scale at Shipston-on-Stour. The ability to identify the large catchment-scale performance of NFRM is a critical evidence gap for FRM authorities seeking to explore the role of WwNP in agricultural uplands (Burgess-Gamble *et al.* 2018: 22, Niehoff *et al.* 2002, Pattinson *et al.* 2014, Bulygina *et al.* 2009, Jackson *et al.* 2008, McIntyre *et al.* 2012).

NFRM was shown to effectively attenuate downstream flood peaks, delaying the time-to-peak and lowering river stage during return periods across most hydrological scales. Nonetheless, the change in Qp was highly variable across the catchment area; the greatest reduction in Qp as a consequence of the co-designed NFRM opportunities were identified in the Knee Brook (- 8.1%), Nethercote Brook (- 8.9%) and the River Stour (- 7.6%) to the index (QMED) flood. In comparison to other modelled NFRM catchments assessed in the meta-analysis of literature (section 2.5.1), the results from the Stour Valley indicate a smaller effect on the flood hydrograph than those tested in other rural headwaters. Many of these projects were tested using an 'ideal' scenario, with no local engagement. Similar performance was shown in the Holnicote Estate (- 10%) and Lustrum Beck (- 12%) schemes, both larger catchments that tested spatially diffuse NFRM opportunities to small flood events (National Trust 2018, Reed and Thomas 2018). The co-designed NFRM opportunities proved less effective, and in most catchment locations largely negligible, to larger events (1%AEP and 1%AEP + Climate Change Allowance) that cause internal flooding to downstream properties and businesses. Only three of the six modelled domains showed a reduction in flood peak to the 1%AEP: the Knee Brook (- 0.6%), Nethercote Brook (- 0.9%) and Pig Brook (- 1%) sub-catchments, with the greatest reduction identified for the smallest sub-catchment, Pig Brook (6.8km^2). This pattern of diminished performance with increasing storm size is common across other projects and flood risk management schemes more generally (Chrisholm 2012).

However, two NFRM studies (both at smaller catchment scales), have identified more considerable reductions in downstream flood peaks. Identified in the meta-analysis (section 2.5.1), the RAFs modelled and monitored in Belford, Northumberland, UK, provided a 30% reduction in Qp to the 1%AEP (Quinn *et al.* 2016, Nicholson *et al.* 2012) across a 6.8km^2 catchment size. The Water Friendly Farming project, designed as a long-term demonstration scheme to test the performance of catchment-wide agri-environment measures, identified an average of 21% reduction in downstream flood peaks to the 1%AEP across the River Thame, UK at a 12.5km^2 catchment size (Briggs *et al.* 2016). However, these are exceptions to other NFRM schemes, which have yet to be tested (particularly through monitoring networks) to such events, which have not identified any peak attenuation and flood risk reduction to larger events.

With regards to the other limited co-designed NFRM schemes outlined in section 2.5.1, the Pontbren, Wales, scheme also provided a reduction in flood peaks (50% and 38% respectively) to smaller events (3.3%AEP). These other farmer engagement schemes, which have also had performance testing, identified a much greater reduction in flood peak compared to the co-designed Stour Valley NFRM opportunities based on comparable return periods. Furthermore, at the furthest downstream extent at Shipston-on-Stour the PGIS-NFRM scenario did not reduce the threshold of flooding below the 3.4m at the 1%AEP and 1%AEP + Climate Change Allowance (outlined in section 6.3.3 and 6.3.4). Therefore, the co-designed NFRM scheme in singularity did not provide significant flood risk reductions, defined by the Environment Agency under Flood Defence Grant-in-Aid criteria as transitioning properties and businesses to a lower risk banding (1%AEP to a 2%AEP) (Environment Agency 2005). Possible reasons for the lesser flood peak reduction (particularly ≥ 1%AEP) in the Stour Valley could include one or a combination of the following factors:

Hydrological Scale

At 187km^2, it was identified that the highly spatially-dispersed NFRM opportunities, were not able to provide an up-scaled aggregation of marginal gains to considerably reduce flood peaks below the threshold required to move properties and businesses out of flood risk. Greater flood peak reduction was identified across the smaller and medium hydrological scales, which adheres to the findings across multiple NFRM evidence reviews (e.g. Ngai *et al.* 2016, Dadson *et al.* 2017, O'Connell *et al.* 2007), including the meta-analysis of literature within this thesis (section 2.5.1).

Testing co-designed features over an 'ideal' NFRM scenario

The framework of this research was based on using active engagement to test a 'realistic' NFRM scenario, as opposed to an 'ideal' set of NFRM techniques. The rationale, outlined in section 3.5, was to shift the focus of WwNP scoping studies away from top-down scopes that often provided little consideration of local stakeholders (i.e. farmers and landowners) and their needs when engaging in local FRM schemes. However, in some areas it was identified there was a minimal engagement for the identification of opportunities, particularly across tenanted farms under arable land management (outlined in section 5 and discussed in section 7.2). Exploration via modelling of clustering a greater concentration of NFRM opportunities through a more targeted approach, based on river response, could have identified a scenario that could provide greater flood risk gains. Johnson (2017) found this to be the case in the Life-IP project across the Eden Valley Dynamic TOP Model schemes; however, frequently the modelled opportunities had to be considerably adapted for the needs of the local farmers and landowners in order to consider adoption. No studies to date have compared 'ideal' vs 'realistic' NFRM opportunity testing. For further research (outlined in section 8) such an investigation would assist practitioners and risk management authorities in better understanding the sort of financial incentives needed to better assist the decision-making around cost and benefits of NFRM, not just for flood risk authorities' capital expenditure, but for farmers to set areas aside for flood mitigation.

NFRM funding varies considerably across the UK, based on devolved policies, strategies and incentive mechanisms for landowners and farmers to explore WwNP. In England and Wales, most long-term funding for farmers is secured through agri-environment schemes based upon the Pillar II payments under the European Common Agricultural Policy (EU 1967). Countryside Stewardship (CS) is the latest Agri-Environment scheme for which farmers are eligible for application based on a competitive basis within the Mid-and-Higher tiers. Within CS there are a variety of a capital grant items that relate to NFRM techniques which farmers could include as part of their applications (outlined in Figure 7.3).

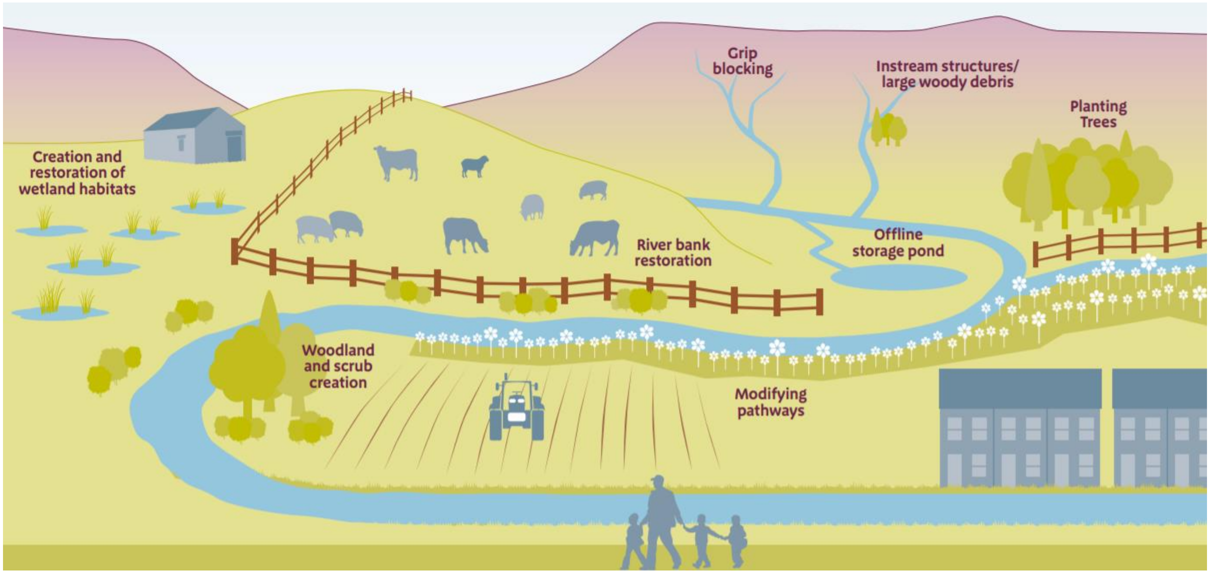


Figure 7.3 NFRM options within Countryside Stewardship (Defra and Natural England 2016).

These schemes are not assessed based on their performance of flood risk reduction, but the priority of such schemes (e.g. afforestation) in that particularly region as set by Natural England. Additional funding is available for those CS applicants who wish to gain technical support and advice on devising an Implementation Plan (PA1) and/or Feasibility Study (PA2). This type of technical advice for farmers and landowners is considered essential for installing NFRM opportunities (Natural England 2018). The Bristol Avon Rivers Trust (BART) and the Somerset FWAG partnered through CS in order to deliver the Bydemill Brook NFM scheme via the facilitator fund, paying for the organisations technical expertise to advise a group of engaged farmers in designing and delivering NFM opportunities (Alvis and Smith 2019). However, performance modelling was not part of the scope of this scheme, with the focus on co-designing for multiple-benefits, without gathering evidence or undertaking a modelled scope of potential flood risk reduction from any scheme. The scheme identified a key challenge with trying to engage farmers who had already renewed their stewardship prior to the programme, or those farmers who did not want to explore agri-environment schemes.

Other payment mechanisms for NFRM vary based on devolved FRM responsibilities. In Scotland, as part of the Rural Development Programme, the Agri-Environment Climate Scheme provides a one-off payment for capital works (i.e. the NFRM interventions themselves), or annual payments for altered land management (e.g. arable reversion) for up to five years (Forbes *et al.* 2016). A similar scheme is available under the Rural Development Programme for afforestation and facilitator payments, in order to fund project officers to work with agencies to deliver NFRM. However, until this research, there remained little guidance for such project officers on how to co-design NFRM opportunities with the most critical stakeholders: farmers and landowners, using PGIS. In Scotland, there is also the SEPA Water Environment Fund and Scottish Natural Heritage Grants that can include feasibility studies and capital costs of works. Often the cost that is most overlooked is the continued maintenance costs of NFRM - known as whole-life-cost (WLC) (Frontier 2013) - when considering the annual responsibilities associated with keeping the schemes operating as designed, e.g. desilting ponds, repairing fencing etc. This thesis did not investigate participants' estimation of WLC; this would need to be addressed in further research (section 8) in order to better understand the different influential factors that determine an 'ideal' NFRM scheme between farmers and FRM authorities.

However, section 6.3 was able to disaggregate the effectiveness of NFRM based on the spatial application (clustered or in singular) at a range of catchment scales to different return periods. Whilst other schemes had identified greatest flood risk reduction at the smaller hydrological scale with the greatest number of storage features (e.g. Tweed Forum 2013, Metcalfe 2016, Owen 2018, Nicholson *et al.* 2015, Wallace and Chappell 2019), this thesis has found a more complex relationship between spatial application and hydrological scale in the Stour Valley. NFRM tested to smaller events (≤ 3.3%AEP) at smaller hydrological scales (≤ $10km^2$) proved most effective at attenuating the downstream Qp. However, the clustering of NFRM opportunities across Sutton Brook with a high number of NFRM opportunities across the upstream tributaries, proved less effective than those delineations with a more spatially diffuse application of NFRM, as the flood peak showed a gain in height in the downstream extent of Sutton Brook as a result of flood peak convergence (section 7.3.1).

7.3.3 Model and data uncertainty

In order to assess the confidence of the modelled results, an investigation into the influence of erroneous data and parametrisation uncertainty on flood peak impacts has been presented.

Uncertainty in localised rainfall-runoff data

Due to the lack of suitable rainfall data within the catchment extent, rainfall events were generated using the FEH to create design events, and calibrated to historic flow records (section 3.6.3). In order to accurately represent spatially variable flow regimes across the catchment extent in hydraulic models, spasmodic rainfall patterns are needed in order to provide realistic inputs into models (Kay *et al.* 2019). The lumped nature of the modelled domains in this study limit the ability of the model to reliably determine sub-catchment rainfall-runoff response, due to the lack of localised rainfall data and storm tracking over the large catchment extent. Figure 7.4 provides a schematic of these processes and requirements refined at the localised site-scale, along with possible flow monitoring to supplement the gauging network across the catchment in order to refine modelled calibration to account for the propagation of flood waves. Section 8 outlines further research to use observed data along with existing models to improve the confidence of NFRM performance.

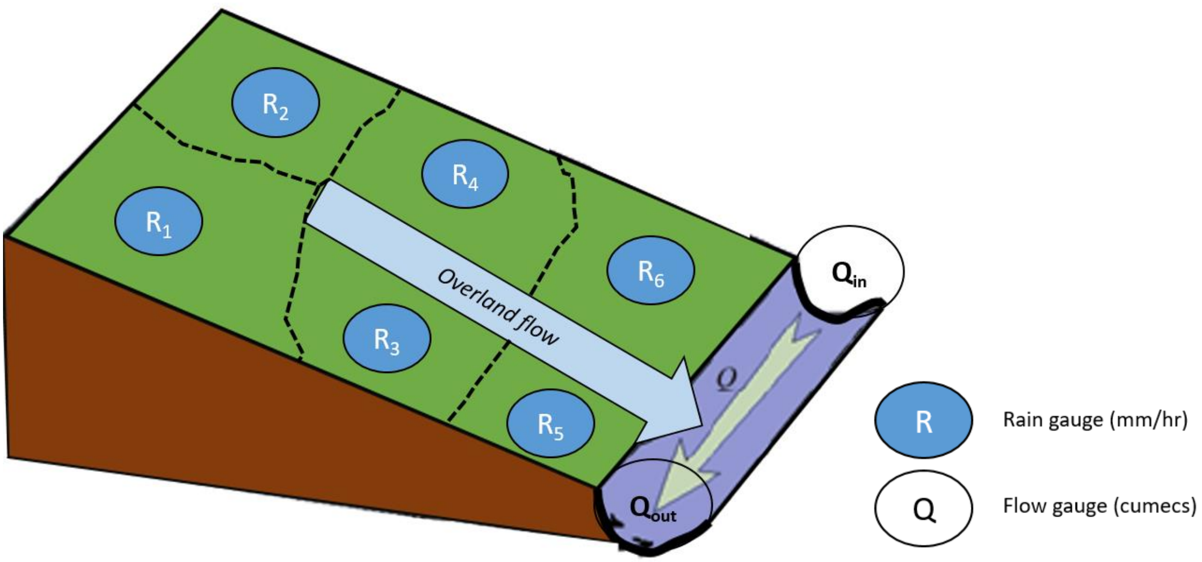


Figure 7.4 Localised, spasmodic rainfall and river response gauging at the site scale to improve modelled confidence and reduce uncertainty

8 Conclusions and Recommendations

8.1 Introduction

This section summarises the main findings and addressed evidence gaps within the thesis, evaluating how effectively the aims and objectives have been met. Suggestions and recommendations for further research are included. Finally, reflections as to whether the research findings have assisted agricultural land management and flood risk policy making matters in relation to NFRM practices are provided. In concurrence with the key research gaps addressed by the aims and objectives: how and where can NFRM opportunities be identified when working *with* farmers and landowners?; and do the modelled tools developed and employed help better understand the performance of NFRM techniques at the large (187km^2) catchment scale to multiple flood risk scenarios?

8.2 Research Summary

As outlined in Chapter 1, the thesis aimed to investigate the possible effects of NFRM on meso-scale hydrological processes, flood risk, and the role WwNP, and the stakeholders that apply them can play through a large-scale application of a Natural Flood Risk Management (NFRM) scheme.

The method developed and applied (section 3) and corresponding results (sections 4 and 5) have provided an insight into the role farmers and landowners can play as invaluable local stakeholders in NFRM schemes, identifying potential opportunities to slow, store, filter and disconnect flood flows through a novel PGIS framework. The study provided a detailed review of the co-design process (section 4), which required the support and introductions of trusted gatekeepers (a local flood action group, Natural England and the National Farmers Union), to enable farmers and landowners (along with supporting participants involved in the PGIS exercises) to undertake a risk-based approach to NFRM planning at large catchment scale. There is, however, a need to carefully consider the participant characteristics as the level of engagement and number of NFRM opportunities was highly varied, particularly between landowning farmers and those under a tenant agreement.

In addition to providing a method on *where* to situate NFRM, section 3 and results chapter 6 also provided an insight into *how* the NFRM opportunities performed across the large catchment scale through hydrodynamic modelling, using limited observed flow data to calibrate a baseline model. The model was delineated to understand rainfall-runoff characteristics, comparing a baseline scenario to NFRM, across multiple return periods. The modelling contributes evidence that NFRM can reduce downstream flood peaks, even at large hydrological scales. However, the effects were greatly diminished to larger events, with a heavy influence of hydrological dilution when the performance testing was up-scaled. The performance of the co-designed NFRM opportunities largely corresponds with many other NFRM studies, as identified in the meta-analysis of literature provided in section 2.5.

The following sections outline the aims and objectives established for attaining the overall research aim; these are outlined below along with a summary of corresponding findings for each aim.

8.3 Conclusions

The conclusions corresponding to each of the thesis's aims and objectives are listed below:

Aim 1: Undertake a desk-based characterisation of the catchment area

The physical, hydrological and social characteristics of the study site were collated and presented using secondary GIS data from mostly open data sources under open government licenses (section 3.4). The characterisation of the catchment enabled the research to provide clipped maps per farm and estate that were included in a Farm Information Pack (FIP) (Appendix D) for each farm and estate visit during the PGIS phase of research (second aim). Physical and hydrological characteristic maps enabled engagement during the PGIS process from an informed (remote, desk-based) position, to contribute towards the decision-making process in identifying sources-pathways-receptors of flood risk. Social characteristics mapped within in the FIPs per farm and estate engaged provided a greater insight into ownership, agri-environment schemes and wider constraints and sensitivities when identifying NFRM opportunities. The remotely generated FIPs were also a consistent template for collating local knowledge and 'ground-truthing' data, facilitating discussion as required during the PGIS exercises.

Aim 2: Identify NFRM opportunities across the catchment area

Utilising the FIPs generated in aim 1 and the PGIS framework, 487 NFRM opportunities were individually co-designed with all landowners and farmers (overview provided in Figure 5.1). Each feature was allocated a GIS shape, line or point file reference, relating to a spreadsheet of all proposals and their 12-figure national grid reference and dimensions (see Appendix E). The sixteen types of NFRM measures provided to farmers and landowners in the NFRM guidance document (Appendix C) were categorised in accordance with the three dominant EA Evidence Directories (Burgess-Gamble *et al.* 2018) terms of reference: Runoff Management, River and Floodplain Management and Woodland Management.

The PGIS framework managed to cover all farms and estates across the catchment area (187km^2), with 129 participants, 38 farmers and landowners engaged as key decision-makers, and a wider 91 consultees including drainage contractors, game keepers, farm/estate managers, family members and tenant farmers of land owned by not farmed by the landowner, to provide their input and advice on potential opportunities. This process was highly iterative and time consuming, taking 14 months to conduct all PGIS exercises will all farmers and landowners, and confirm the final NFRM opportunities per farm and estate that participated in the research. The co-design method was also detailed and reviewed in sections 3.5 and 4 respectively, to detail the data and engagement techniques needed to facilitate active engagement with these often under-involved participants in NFRM decision-making.

Once all NFRM opportunities were co-designed, mapped and agreed, a variety of physical, hydrological and social factors (most of which determined in the desk-based study meeting the first aim) were assessed in relation to their influence on the number of NFRM opportunities. Statistical tests for association between these factors and the number of opportunities highlighted some influential factors other NFRM schemes could consider. Most notably, there was a significant relationship between NFRM opportunities and land ownership, with more NFRM opportunities co-designed in farms and estates that were owned rather than those that were tenanted.

Land cover and land use were also significant factors in the situating of NFRM opportunities, with NFRM more commonly situated in areas of grassland and pastoral farming instead of arable farms. However, unlike other desk-based NFRM opportunity mapping studies, the areas of the catchment with a high capacity for infiltration (HOST class 2 and free draining limestone) did not influence the number of NFRM opportunities. The RoFSW desk-based data was heavily used to guide the participants during the PGIS process, particularly when situating runoff management opportunities. Yet, many farmers and landowners also found erroneousness flow pathways that were 'ground-truthed' by the farmer using their own experiences and flood memories.

Aim 3: Model the performance of the PGIS-NFRM scenario to multiple storm events

The hydrodynamic modelling of NFRM performance using xpswmm © and Flood Modeller Pro © enabled the assessment of NFRM performance to variable hydrological scales and return periods. Analysis of catchment response pre and post NFRM enabled the following hydrological responses to be considered: the lag time of the catchment (Tp); assessing the propagation of flood waves through the catchment; and overall flood peak (Qp) attenuation across multiple hydrological scales from small upstream delineations, to the total catchment extent at Shipston-on-Stour where the model was calibrated. The PGIS-NFRM opportunities had diminishing effects on the downstream hydrograph response to the larger flood events, this was especially the case for the 1%AEP + climate change allowance. However, across all hydrological scales the co-designed NFRM scheme was able to alter the downstream hydrograph response to smaller events (QMED – 3.3%AEP), with influence from hydrological dilution the larger the scale of performance assessment. This adheres to wider literature findings of NFRM performance across fluvial (non-tidally influenced) basins, which have also identified diminishing effects to larger hydrological scales. The relative sub-catchment timings of peaks were also considered a risk for NFRM application to the Sutton Brook headwaters delineation, with a reduction in time-to-peak and heighted hydrograph response due to converging tributary responses. Studying local time series of flow data in this method greatly provided an insight into a more targeted approach if risk management authorities pursued an approach to delivery and in-situ monitoring.

Furthermore, it is important to sustain local engagement and relationships with farmers and landowners to continue the active engagement around modelled results, to 'locally calibrate' and refine catchment understanding further. Hence open access and telemetered hydrological data to support wider understanding are fundamental to NFRM delivery and will be discussed further in section 8.4. This aims to reduce model uncertainty and improve confidence with a greater resolution of catchment rainfall and runoff response to a more detailed and delineated scale, advocated by many hydrological studies in catchment scale NFRM and altered land use management methods (e.g. McIntyre *et al.* 2013, Ngai *et al.* 2018, Dadson *et al.* 2017). As outlined in section 7.3.3, the modelling method had issues with homogenisation of catchment response using the FEH design storms as inputs. The lack of localised rainfall and runoff data required FEH data to be used as design event inputs and calibrated to the furthest downstream extent of the study site (the National River Flow Archive Gauge, in Shipston-on-Stour), which was a key limitation for assessing varied antecedent conditions during an event and the effects on catchment saturation. Current evidence reviews indicate there is diminishing effectiveness of interventions the more saturated the catchment becomes (section 2.5.1); the modelled analysis was unable to deconstruct the hydrograph and assess this influence due to the lack of observed antecedent data including infiltration rates and evapotranspiration losses.

8.4 Recommendations and Future Research

Whilst this thesis has addressed two critical research gaps using the Stour Valley, Warwickshire-Avon:

- Identifying where NFRM can be situated using participatory GIS with farmers and landowners;
- The performance of a co-designed scheme to multiple storm events and hydrological scales

There are still further gaps that have been identified from the research findings, particularly around further engagement mechanisms with stakeholders (sections 8.4.1), and collection of observed data in order to improve modelling methodologies and reduce uncertainties (section 8.4.2). Furthermore, recommendations for a more integrated approach to agricultural land and water policy are provided, linking to further research requirements into the wider ecosystem services from NFRM (section 8.4.3).

8.4.1 Follow up engagement: close the loop

The use of farmers and landowners as part of this research approach was able to provide valuable local knowledge in order to map locally feasible NFRM opportunities. However, further qualitative research methods would assist in better understanding participants' local motives and barriers to adopt NFRM. Holstead *et al.* (2014), Kenyon and Langan (2011) and Posthumus *et al.* (2008) conducted focus groups with farmers and landowners in catchments exploring NFRM; each study identified common barriers to NFRM, principally policy landscape (further discussed in section 8.4.3), evidence and financial implications of the whole life costs to the farm business (linked to the policy incentives). A series of focus groups with farmers and landowners would greatly assist in recording their attitudes and motives towards NFRM that manifest in the co-designed NFRM opportunities per farm and estate.

In terms of NFRM application, it is advised to use a trusted mediator to inform farmers and landowners of the modelled results of the co-designed NFRM opportunities. The ability to 'close the loop' when undertaking active engagement enables any iterations to be made to each scheme in order to review and adapt based on the evidence (outlined in Figure 8.1), as well as ensuring farmers and landowners are continually involved in the full research life-cycle from idea generation to practical execution (Speller 2005, Cook *et al.* 2016). Howgate and Kenyon (2009) identified open communication around all stages of evidence development as a crucial technique for sustainable flood risk management. This could involve conducting focus groups based on catchment delineations, ensuring farmers and landowners take ownership of their local tributary and the corresponding catchment response. The modelled methodology and results could be hosted and shared on an online GIS portal to encourage full knowledge exchange between the scientist and farmer/landowner (Wilkinson *et al.* 2015).

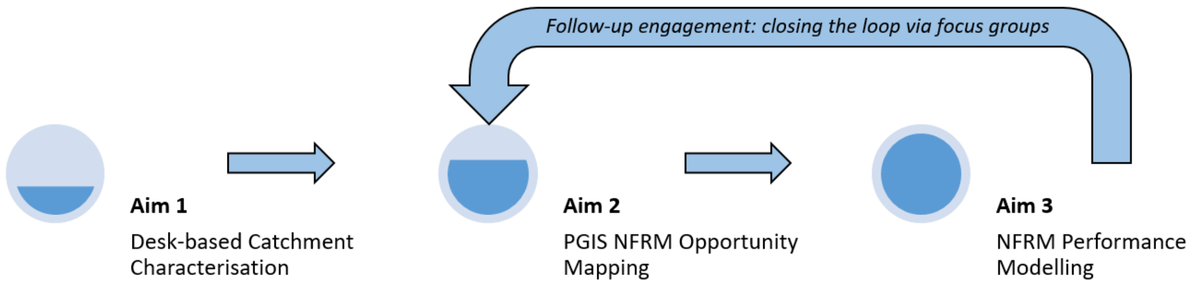


Figure 8.1 Further research with farmers and landowners, closing the loop and sharing evidence

8.4.2 Observed data and updated modelling

Whilst this thesis made considerable contributions to knowledge regarding NFRM performance to multiple return periods across hydrological scales, there is certainly still a need to build upon the limited observed data network within the catchment. Such detail at the local/feature scale would enable a much more refined understanding of the large catchment's spasmodic rainfall and highly variable runoff patterns. Thirty-six rain gauges to each delineation < $10km^2$, and seventy-two flow gauges at each delineations inflow and outflow, would considerably improve the upstream monitoring network of observed data to use as inflows and more detailed flow gauges for calibration. Telemetered rainfall flow gauges would considerably assist in obtaining continuing data, particularly for high-flow events that are considerably more challenging to record (Beven *et al.* 2019, Aronica 1998). The ability to gather rainfall and runoff data across refined local hydrological scales can also improve the ability to refine model parametrisation, using observed data to test the influence of different parameters within each delineation, for example changing land use, features and infiltration.

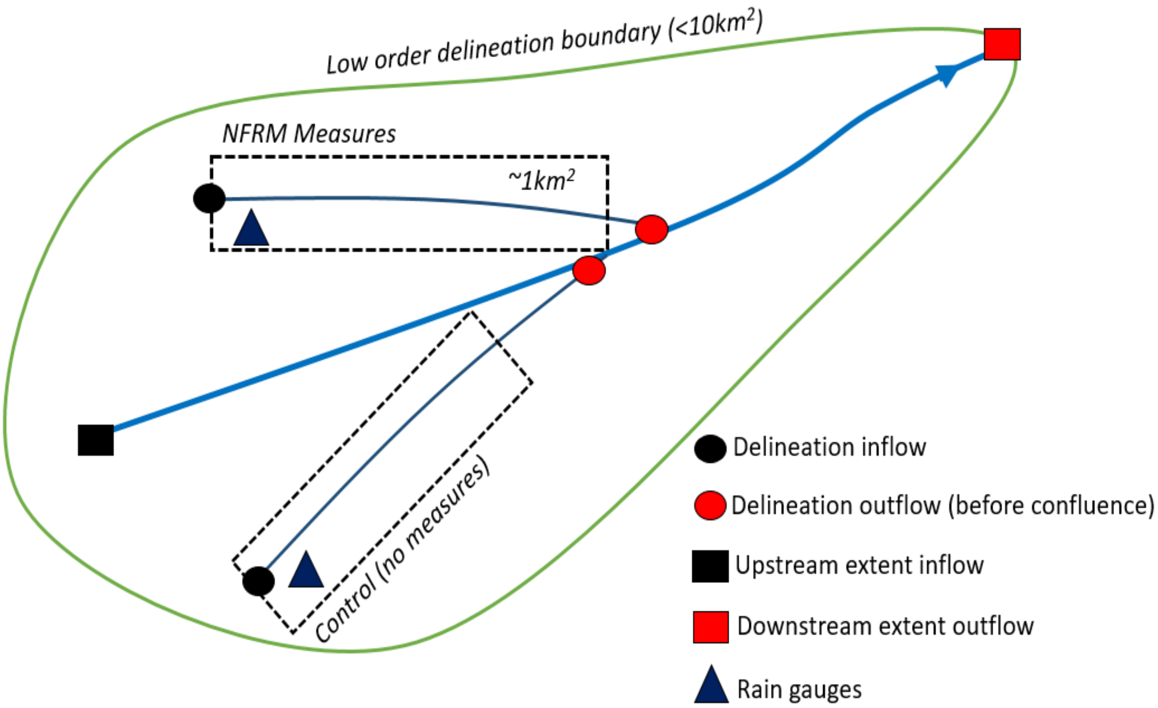


Figure 8.2 BACI monitoring strategy for observing NFRM performance

In terms of NFRM application, a before-after-control-impact (BACI) monitoring strategy would enable a comparison of two similar (donor) hydrological regimes within the catchment (outlined in Figure 8.2). Arnott *et al.* (2019) recommended this practice for the *Defra Catchment Laboratories* in order to understand the role of NFRM on catchment response: comparing a tributary with NFRM to a tributary without, evaluating hydrological response across (ideally) the same storm (and duration) and characteristics with NFRM techniques as the only variable. Each outflow would need to be upstream of the downstream confluence in order to minimise hydrological dilution and corruption of the gauge readings (Chappell *et al.* 2017, Owen *et al.* 2012, River Restoration Centre 2012). As part of the Rivers Trust catchment wide monitoring of NFRM, Evans *et al.* (2014) also recommend the use of community monitoring methods in order to obtain in-situ evidence of NFRM techniques. Farmers and landowners, as well as local community members, could provide images and videos of flood heights and storage provided by pilot NFRM schemes in order to obtain in-situ evidence to supplement quantitative monitoring networks (Flow Partnership 2017, Addy *et al.* 2015).

With the use of more detailed observed data, there is an opportunity for the FEH rainfall-runoff design storm event method applied in this research to be advanced into a more transparent and robust process of managing and manipulating the downstream hydrograph through NFRM optioneering. The current model homogenises the upstream delineations and simply scales sub-catchment FEH hydrographs from the upstream into the next downstream domain via a routing model. The time-to-peak adjustments across the large catchment area also shifts the GUIH in a lumped linear manner, whereas catchments would respond in a more nonlinear manner (Beven *et al.* 2020). This could reduce influence of factors such as model equifinality (outlined in section 7.3.3), that an output can be reached by many processes (Aronica *et al.* 1998, Beven *et al.* 2014, Beven 2006a, Beven 2006b).

8.4.3 Integrated Management of Agricultural Land and Water: Policy and Practice

This thesis has addressed subjects regularly posed by RMAs and policy makers managing NFRM projects. The combination of local engagement and hydrodynamic performance modelling at the large catchment scale have developed and tested a method for co-designing and investigating NFRM to assist in underpinning scoping and investment strategies, particularly in light of an ever increasing impetus on payment for public good (Raymant 2019). The detrimental influence of existing stewardship areas and stakeholder confusion of their role under the Land Drainage Act (1991) when co-designing NFRM highlights the need for agricultural land use polices to encourage systemic strategies that utilise NFRM techniques for public good, going beyond FRM, and encompassing wider ecosystem services, including: pollution control, climate resilience, carbon sequestration, health and well-being, quality of life, thus providing multi-benefits (Pagano *et al.* 2019). Further research exploring and particularly valuing these multiple benefits as possible drivers and trade-offs for farmers and landowners could assist in developing the ‘payment for public good’ principles advocated in the new Environmental Land Management Scheme, superseding the EU Common Agricultural Policy.

Furthermore, this study identified the disproportionate impacts of flood events on the farmers themselves, with some farmers and landowners occupying land at much greater likelihood of inundation, and therefore, associated business disruption. Based on the PGIS NFRM opportunity mapping results in this thesis, there is scope for enabling suitable policy measures that pay in accordance with these highly inundated (Less Favourable Areas), including differential payment rates for different land management techniques. Such altered remunerations would acknowledge the agricultural productive disadvantage, as well as NFRM opportunities, from these highly inundated pathways of pluvial and fluvial flood risk.

The Land Use Policy Group (LUPG 2009, LUPG 2018) advised that any changes in funding needs to differentiate two forms of NFRM. Firstly, the measures that do not incur any additional costs (capital and whole life) to the farmer should be known as 'best practice'. This includes wider practices such as conservation tillage, riparian buffering and reduced stocking density that is advised under current agricultural guidance (Environment Agency 2009, Defra 2009a, Defra 2016). Secondly, the more 'intrusive' NFRM techniques needed as part of a CBFM plan to address downstream flood risk should be regarded as high whole-life costs to the farmers and landowners. Where these changes deliver wider public value, they will necessitate significant long-term remunerations to incentivise farmers to adopt NFRM who are currently under associated agri-environment schemes. Existing payments under Countryside Stewardship (formerly Environmental Stewardship), within the Pillar II policy umbrella equate to 'profit foregone' payments to the farmers and landowners undertaking environmental-betterment for their farms and estates as part of the EUs Rural Development Programme. However, as outlined in section 2.2.3, there is a diminutive body of evidence of 'profit foregone' payments being utilised for NFRM schemes. Most NFRM schemes in England and Wales have been delivered through national FCERM capital investment for pilot projects (e.g. Defra's £15 million investment into NFRM), and some as part an FCERM scheme that reduces the number of properties and businesses at risk (known as Outcome Measures 2 as part of the Environment Agency's Partnership Funding Calculator). In England, Wales and Ireland, LLFAs and IDBs have the power to gather levies from farmers under the LDA (1994) to fund NFRM.

This considerable level of local engagement in this research established that collaboration between farmers, residents and businesses at risk of flooding could enable localised investment in upstream NFRM purposes based on available and continually gathered evidence (section 7.3 and section 8.4.2 respectively). Such arrangements would require a more holistic integration across all forms of policy and investment, and a shift from traditional river-basin flood defence strategies. Using a local flood action group and agencies as gatekeepers to famers and landowners provides an interface recorded through the PGIS process between regional (top-down, desk-based) and local (bottom-up, local knowledge) spatial planning and agricultural land management considerations. However, Pillar I of the CAP should also be concerned with 'flood-proofing' (in addition to such incentives in Pillar II) at both an international and national/regional/local level to ensure that flood risk is not enhanced in some areas and abated in others. As such, under the Environmental Land Management Scheme (ELMS) (replacing the Single Farm Payment scheme in 2024), it is recommended that remunerations currently paid in the form of Pillar I payments should be assessed alongside 'local' initiatives that could provide greater public-value, with particular attention paid to FRM gains associated with wider multiple-benefits across ecosystem services.

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