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Quantifying the efficacy of Natural Flood Management in agricultural headwater catchments

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A dissertation submitted to the University of Bristol in accordance with the requirements for award of the degree of Doctor of Philosophy the Faculty of Science

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Abstract

Natural Flood Management encompasses a range of measures which aim to restore hydrological and morphological catchment features, slow, store, and filter hillslope and channel flows and decrease downstream flood risk. Whilst traditional forms of flood management have an extensive evidence base to inform their design and management, there is currently only a small quantity of datasets that characterise and assess the function, and impact of more natural forms of flood management. In response, this thesis presents multiple chapters that have assessed the function and impacts of a range of NFM measures, including a focus on the role and implications of design, function, and management, though the analysis of generated empirical datasets for agricultural SW-England headwater catchments.

An event definition methodology was developed to separate rainfall events and quantify the impact of channel-based NFM structures for storing and slowing flow. During the largest recorded events, marked peak flow reduction downstream of offline water storage ponds (up to 7%) and leaky woody dams (up to 56%) was shown. An assessment of NFM management tasks highlighted the marked impact of site maintenance to sustain the storage function of an online pond site, where outflow management was demonstrated to have a greater impact on flow storage than the recorded rainfall inputs. Evaluating the impact of subsoiling for NFM through single-ring infiltration and rainfall simulation methods demonstrated the potential for targeted agricultural management to reduce overland flow, despite high observed inter-field variability.

This thesis contributes to the UK NFM empirical evidence base, presenting case study examples and quantified hydrological parameter values that have analysed the impact of NFM measures in response to rainfall. This information is important for use as observational data in future modelling applications and to provide design and management recommendations for future NFM applications.

Dedication and Acknowledgements

I am hugely grateful to a lot of people who have made this thesis possible!

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Author’s Declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's *Regulations and Code of Practice for Research Degree Programmes* and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: Tamsin Lockwood   DATE: 11/03/2022

Table of contents

List of tables

List of Figures

List of abbreviations

BD	Bulk Density
CAP	Common Agricultural Policy
CFG	Community Flood Group
DEM	Digital Elevation Model
ELJ	Engineered Logjams
ELM	Environmental Land Management
FAS	Flood alleviation schemes
FWAG-SW	Farming and Wildlife Advisory Group, South-West
NBS	Nature Based Solutions
NFM	Natural Flood Management
RAF	Runoff Attenuation Feature
SF	Sediment Flux
SSC	Suspended Sediment Concentration
SEPA	Scottish Environment Protection Agency
SfM	Structure from Motion
SFM	Sustainable Flood Management
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SY	Sediment Yield
TFM	Technical Flood Management
V	Volt
WWNP	Working with Natural Processes

1. Context

1.1. Introduction

Land drainage, reclamation and conversion to agriculture, alongside rising population pressures from as early as the end of the 1800s resulted in what is now often considered the first widespread anthropogenic fluvial food management, occurring across much of the UK (Werritty, 2006). Into the 1900s and particularly following the Second World War, the introduction of the Common Agricultural Policy and drive for self-sufficient food production, had large-scale impacts on the UK landscape (O'Connell *et al.*, 2007; Wheater and Evans, 2009; Marshall *et al.*, 2014; Mehring *et al.*, 2018). This is evident from river channel modification (eg. channelisation), woodland and hedge loss, and soil degrading farming practices, such as the use of heavy farm machinery and the creation of tramlines and farm tracks (O'Connell et al. 2004). Whilst aiming to increase agricultural productivity, these land use changes and landscape modifications, including urbanisation, are now widely accepted to have generated significant flood risk increases in the UK in recent decades (Nicholson *et al.*, 2012; Dadson *et al.*, 2017; Norbury *et al.*, 2021).

Global concerns regarding flood risk increases gained increasing recognition in the 1990s and 2000s due to newly published climate and economic projections, which highlighted the increased likelihood of intense rainfall and rising flood damage costs (Pescott and Wentworth, 2011; McLean *et al.*, 2013). This pattern is largely representative of trends globally and is reflected in a rise in publications that highlighted these issues of flood risk increases (see Figure 1.1).

Within the UK, in response to these increasing flood risk concerns, new and adaptive methods to reduce flood risk were examined, including notable additions to policy since the 2000's and over the following years. A number of these key additions are summarised by Table 1.1. In the summer of 2007, wide parts of the UK were hit by extensive flooding, which too has been widely considered as a pivotal moment in UK flood management policy (Collentine and Futter, 2018; Short *et al.*, 2019). Following these floods, the Pitt Review (2008) was produced, which importantly highlighted the need to modernise flood risk legislation, introducing the importance of working with, rather than against natural processes and responding to flood risk from a whole-catchment perspective. Importantly, the Pitt Review made key recommendations for developing water slowing, retention and storage (Pitt, 2008). Conventionally in the UK, flood management has comprised of two complementary methods: flood alleviation schemes (FASs) and flood defences. FASs broadly focus on increasing water capacity upstream and enforcing flow control downstream, for example, through the construction of reservoirs and constrained outflows (Norbury *et al.*, 2021). Flood defences typically involve the construction of barriers between river channels and areas designated to be protected from flooding, such as urbanised areas (Pepper *et al.*, 2002). However, the Pitt Review was key in stressing the inadequacy of using solely these hard engineering methods to respond to flood risk. This was particularly relevant in the context of achieving longer-term sustainability and thus the importance of responding to both climate change impacts and urbanisation.

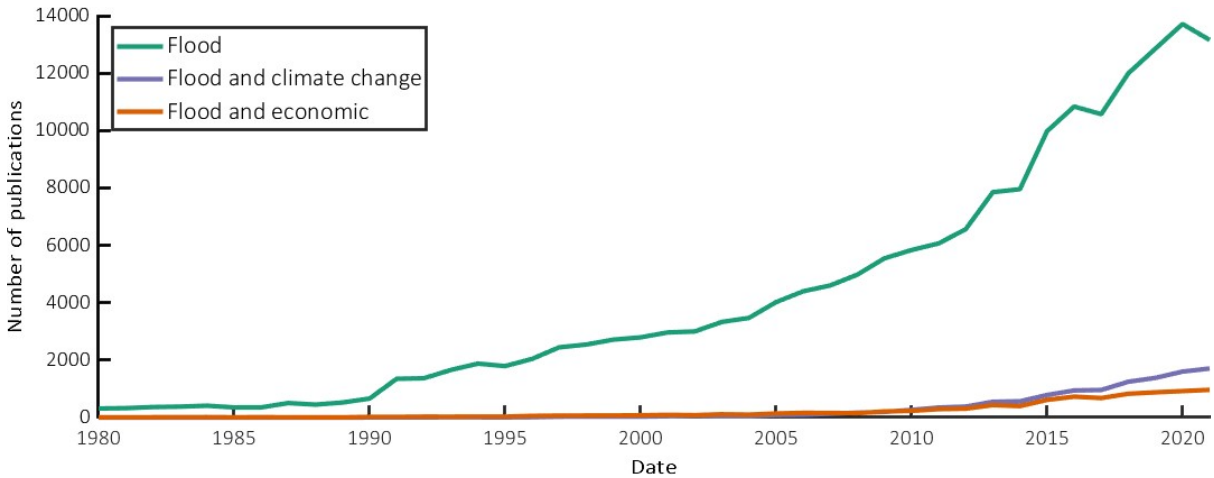


Figure 1.1. Number of scientific publications published per year since 1980 that include the following keywords (search term “flood*”), flooding and climate change (search term: “flood*” AND “climate change”) and flooding and the economy (search term: “flood*” AND “econom*”). The number of publications is based on a Web of Science search until 2021.

Year	Policy	Implication
2005	‘Making Space for Water’ strategy in England included Catchment Flood Management Plans (CFMPs)	Introduced ideas where flood risk could be managed across the whole catchment, alongside other strategies such as improved land use planning and flood risk assessments.
2007	European Directive on the Assessment of Management of Flood Risk	Introduction of ‘Natural Flood Management’ in the UK.
2009	Flood Risk Management Act (Scotland)	Driver of NFM opportunity mapping and a more integrated and sustainable approach to flood management. This included the explicit examination of NFM options.
2010	Flooding and Water Management Act (England and Wales)	Used broader terminology regarding the enhancement of natural processes to manage flood risk.
2011	Catchment-based approach’ (CaBA),	Integrated water management initiatives where catchment partnerships were led by host organisations.

Table 1.1. Summary of key additions to policy from 2005 that were key in driving the expansion and adoption of NFM within the UK. Information sourced from: DEFRA, (2005); Falconer and Harpin, (2005); Pescott and Wentworth, (2011); McLean *et al.*, (2013); Barlow *et al.*, (2014b); SEPA, (2015) and Wingfield *et al.*, (2019).

The following years saw successive changes to flood risk management in the UK (Table 1.1). In the past decade, the use of NFM terminology and ideas has seen marked expansion within UK policy, along with, consideration and application within wider flood management, for example forming a key part of CaBA in England (McLean *et al.*, 2013; Norbury *et al.*, 2021). This growth in momentum and rise in the use and application of NFM and wider terminology is reflected in a rise of relevant scientific publications in recent years (see Figure 1.2). The range of NFM features that have deployed across the UK is large, and frequently overlaps with measures that fall into Working With Natural Processes or ecosystem services approaches (McLean *et al.*, 2013; Dadson *et al.*, 2017; Bark *et al.*, 2021). Collectively they can be seen as mitigation strategies that aim to restore hydrological and morphological catchment features, to enhance downstream flood resilience (Lane 2017). Particularly for applications outside of the UK, the wider umbrella term of 'Nature Based solutions' (NBS) has been particularly dominant in these newer approaches to flood management. NBS broadly encompasses any measure or action to enhance ecosystem services (Keesstra *et al.*, 2018), of which flood management may form an aspect of. For example, based on Web of Science searches for up until the end of 2021, 71 studies were returned with 'Natural Flood Management' in the abstract, only 4 of which were from non-UK based studies. In contrast, for searches with 'Nature Based Solutions' and "flood" in the abstract, of the 179 results, 7 of these were non-UK based.

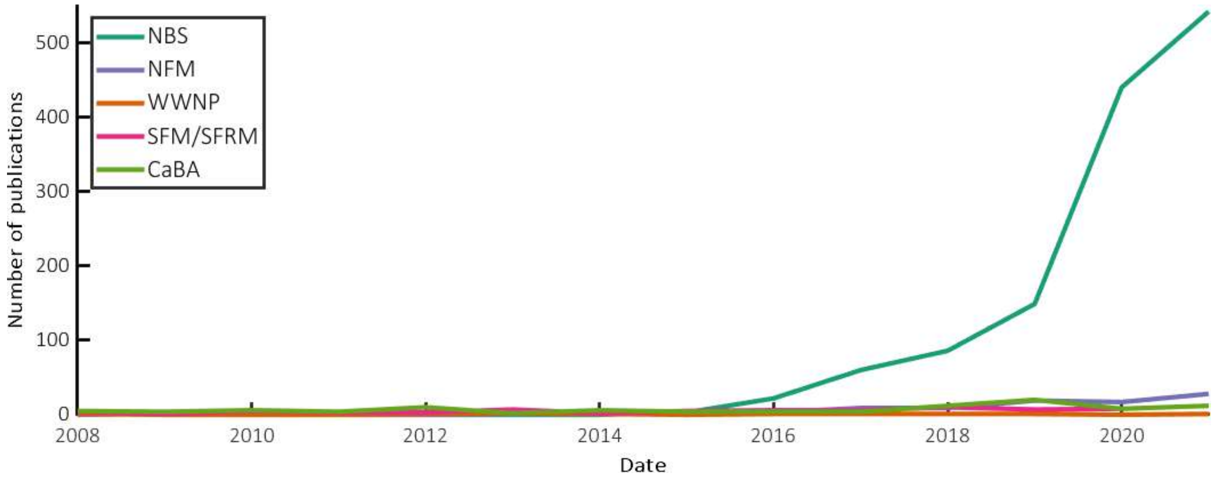


Figure 1.2. Number of scientific publications published per year since 2008 that include the following key words: Nature Based Solutions (search term "nature based solutions"), Natural Flood Management (search term: "natural flood management" OR "natural flood risk management"), Working with natural processes (search term: "working with natural processes"), Sustainable flood management (search term: "sustainable flood management" OR "sustainable flood risk management") and Catchment-based approach (search term: "catchment-based approach" OR "catchment based approach). Number of publications based on Web of Science search up until the end of 2021. Search and plot based on those produced for NFM and wider terminologies (eg. Stratford *et al.*, 2017; Wilkinson *et al.*, 2019; Swanson *et al.*, 2021).

Within the UK, in recent years, further opportunities and expansion are highly anticipated in England through new agro-environmental policies, including the new Environmental Land Management scheme (Bark *et al.*, 2021; DEFRA, 2021a). This primarily involves the transition away from the Common Agricultural Policy (CAP) and introduction of three new environmental land management schemes. These cover small-scale, local practices to increase the sustainability of agricultural activities through firstly, the 'Sustainable Farming Incentive', to include a reduction in pesticide use and increase in soil husbandry. Secondly, 'Local Nature Recovery', will involve financial incentivisation to make space for nature on farms, to include NFM. Finally, at the largest scale, 'Landscape Recovery' will include larger land use change and habitat restoration, for example large-scale tree planting and peatland restoration (DEFRA, 2021b). Under DEFRA's 25 Year Environment Plan and the UK's 2050 net zero emissions targets, these schemes are expected to result in considerable expansion and uptake of NFM within wider 'Local Nature Recovery', which are launching in 2024, following a period of scheme trials (DEFRA).

This marked shift in public and policy perceptions of flood risk management, particularly in regards to whole-catchment approach to flood risk reduction, has seen a huge rise in the quantity and distribution of NFM schemes across the UK in recent years (Rouillard *et al.*, 2015; Cook *et al.*, 2016; Lane, 2017). In response there has also been a rise in the quantity of literature that have documented and analysed these measures (Wingfield *et al.*, 2019; Connelly *et al.*, 2020). The creation of a knowledge base is vital for informing future flood risk decision making, in particular for the role that NFM may continue to play in policy. Notably, NFM has frequently been coupled with and funded under other environmental and ecological issues, including water quality and biodiversity, in order to benefit a wide range of ecosystem services (Rouillard *et al.*, 2015; Keesstra *et al.*, 2018).

These approaches include ponds that increase water storage areas, leaky woody dams that increase friction and reduce channel velocity, woodland creation that improves soil infiltration and features that trap or divert runoff by intercepting overland flow (Pescott and Wentworth, 2011; Bracken *et al.*, 2016). This expansion in NFM include projects, where the catchments have gained high profiles and have been increasingly cited within the literature, including Pickering (Nisbet *et al.*, 2015a; Thomas and Nisbet, 2016), Belford (Wilkinson *et al.*, 2010a, 2010b; Barber and Quinn, 2012; Nicholson *et al.*, 2012, 2019; Quinn *et al.*, 2013) and Holnicote (Hester *et al.*, 2014).

The design and impacts of NFM structures are not as replicable or currently understood as traditional, hard engineered structures, which are based on a well-established, historical database of evidence. NFM structures present a number of key differences to conventional flood management, not least that they are typically built with a flexible design, based on natural processes, are smaller and ideally positioned widely across a catchment. Moreover, NFM measures are currently being constructed, developed and managed based on a dynamic knowledge base that is still under development (McLean *et al.*, 2013; Iacob *et al.*, 2014; Ellis *et al.*, 2021). NFM behaviour is expected to depend on numerous factors, including: catchment characteristics, structure design, management required, and the hydrological conditions experienced (Wahren *et al.*, 2009; Deasy *et al.*, 2014). Thus, the limited amount of datasets quantifying NFM function and impact, in particular peer-reviewed evidence, is not necessarily applicable at all other potential sites or catchments (eg. see JBA, 2021). This is a key constraint and limitation of developments in our understanding of the impact of NFM for downstream flood risk at the catchment scale. Indeed, to characterise NFM features within modelling frameworks, observational data are required that has quantified the processes associated with the features and catchment being examined. Therefore, to investigate catchments over a diverse range of soil types, topography, size, and hydrological conditions, greater numbers and ranges of empirical datasets are required that have quantified NFM behaviour, including key hydrological parameters that can be used to assess flood risk (Pescott and Wentworth, 2011; Dadson *et al.*, 2017; Ngai *et al.*, 2017).

To respond to these current uncertainties and knowledge gaps in the NFM evidence base, the generation of empirical evidence and case studies are consequently of huge, critical importance. Current conventional flood management approaches, such as those introduced here under flood alleviation schemes (FASs) and flood defences, are widely designed, and implemented under a historic and extensively quantified evidence base, associated with widespread confidence (Howgate and Kenyon, 2009; Bracken *et al.*, 2016). A similar level of robustness and certainty is required in newer NFM approaches. The production of a comprehensive and comparable evidence base for NFM measures will allow for robust recommendations for future NFM design and an understanding of the function, impact, and efficacy of different features, to including the impact of factors such as catchment and scale. This will provide information on how NFM may be best included within future flood risk policy.

To contribute to this call for evidence, this thesis has investigated the function and efficacy of a number of different NFM measures, to quantify their effectiveness according to key hydrological parameters. This study was conducted in the Tone and Parrett catchments, SW-England, where since 2014, NFM has formed a marked aspect of the Hills to Levels project: a catchment-based partnership between Somerset's farmers, and a number of environmental organisations (see FWAG-SW, 2018). These were largely formed in response to the widespread flooding in the winter of 2015-2016, that also affected widespread parts of the UK (Stratford *et al.*, 2017; Lavers and Charlesworth, 2018). The individual structures and techniques carried out in these catchments are typically based on site-specific designs that were developed and implemented through Hills to Levels. However, as a collection of NFM they are widely representative of the range of NFM measures and sites that have arisen in recent years (eg. Scottish Environment Protection Agency, 2013; Lane, 2017; Burgess-Gamble *et al.*, 2018).

The contents of this thesis are presented in eight chapters. Following the introduction and literature review (chapter 1), Chapter 2 introduces these sites and the key methodological approach and experimental framework taken to achieve the defined research aims and objectives is presented. This includes additional detail on the study catchments and wider project not included within specific chapters, along with rationale behind study site selection, the field sites selected, and the key field methods carried out. The following four research chapters (chapters 3-6) detail the empirical evidence and analysis conducted, specific to these nine sites. The final chapters of this thesis are a synthesis (chapter 7), where the datasets and evidence produced in the four main research chapters are then drawn together. This places the produced work into context with the literature introduced in chapter 1.2, also highlighting uncertainties. Then finally, the conclusion (chapter 8) provides an overall summary of the results produced in this thesis and highlights where and how the defined research questions have been addressed and provides suggestions for future work.

1.2. Literature review

The following literature review examines our current understanding of NFM and the evidence for its efficacy, based on empirical and modelling based studies, with a particular focus on UK case studies. Natural Flood Management is firstly introduced, largely in the context of UK policy, where NFM types are categorised according to key hydrological parameters (section 1.2.1). The current evidence and methodological frameworks within the literature are then examined (section 1.2.2) with regards to NFM features that are primarily attenuation (section 1.2.3), velocity reduction (section 1.2.4), runoff control (section 1.2.5) and infiltration increase (section 1.2.6) based. This enables the key methodological and research gaps to be identified and summarised (section 1.2.7).

1.2.1. Natural Flood Management

Natural Flood Management represents a range of mitigation measures that largely work with natural processes to restore and augment hydrological and morphological catchment features, to enhance downstream flood resilience (SAIFF, 2011; Nutt, 2012; Dadson et al. 2017; Lane, 2017). As a catchment-based approach to managing flood risk, NFM importantly represents a shift from traditional 'technical flood management' (TFM), which characteristically targets management directly at the issue to be resolved (eg. constructing a flood-defence wall at the site of flooding). TFM has been found to largely reflect an attitude by which humans can control the whole river system, where in reality it may simply transfer flood risk from one location to another (Bracken *et al.*, 2016; Cook *et al.*, 2016).

Despite this widely cited 'paradigm shift' to more sustainable forms of flood management, including NFM, including in recent years (Werritty, 2006; Rouillard *et al.*, 2015; Wilkinson *et al.*, 2019; Bark *et al.*, 2021; D'Souza *et al.*, 2021), the definition and boundaries between flood management types is generally very variable. In the literature, 'sustainable flood management' (SFM) is referred to as a middle ground between TFM and NFM when categorising flood risk management (Cook *et al.*, 2016). However, in plans as well as practice, TFM and NFM are more likely to be coupled (Bracken *et al.*, 2016), and indeed recent recommendations under NFM tend to highlight future policy whereby NFM and TFM coexist in the landscape (Waylen *et al.*, 2018; Wingfield *et al.*, 2019). For instance, this may indicate where many, small-scale NFM features are distributed across a catchment, to complement urban flood defences downstream (Norbury *et al.*, 2018). However, currently how this may occur in practice and in future policy is uncertain, with a number of areas of indecision still to be resolved, including whether NFM structures that require substantial construction are in fact 'natural' or 'working with natural processes' at all, and whether they should be categorised as hard engineered features (Bracken *et al.*, 2016).

The catchment-based approach adopted through the expansion of NFM projects has also been accompanied by a rise in 'bottom-up' flood management (Mehring *et al.*, 2018). This relies on stakeholders throughout the catchment for scheme inception, promotion, confidence and future success (Howgate and Kenyon, 2009; Short *et al.*, 2019). This has produced a particular focus on community engagement, landowner cooperation and in a number of cases, 'Community Flood Groups' (CFGs), where schemes are managed or supported by action plan volunteer groups, providing local knowledge and cooperation (Old *et al.*, 2018; Garvey and Paavola, 2021; Newson *et al.*, 2021). Community-based NFM has highlighted the importance of coordination throughout the whole catchment, to utilise different land uses and measures to store and slow flow (Waylen *et al.*, 2018; Connelly *et al.*, 2020; D'Souza *et al.*, 2021), whilst also gaining from wider benefits, such as habitat creation and pollution control (Black *et al.*, 2021).

The ideas, aims and outputs within Natural Flood Management are conducted using a wide range of terminology globally (Burgess-Gamble *et al.*, 2018). Within the literature, terminology including and incorporating Natural Flood Management processes are used interchangeably, to include Making Space for Water, Nature Based Solutions (NBS), Working with Natural Processes (WWNP) and Building with Nature, often with large discrepancies in how structures and schemes are categorised (Dadson *et al.*, 2017; Lane, 2017; Burgess-Gamble *et al.*, 2018). Particularly in studies outside of the UK, NFM is commonly referred to within the context of Nature Based Solutions (NBS). NBS encompasses all schemes that function to provide environmental benefits for societal challenges (for example, green roofs in cities and coastal habitat restoration (Keesstra *et al.*, 2018; Padma *et al.*, 2019; Xie and Bulkeley, 2020)). These may also fit in, wider again, with Working with Natural Processes (WWNP) that encompasses any work that involves the emulation of natural processes (for example, for flood management as NFM features, or for rationales such as coastal and sand dune management (Barlow *et al.*, 2014b; Environment Agency, 2017)). This categorisation chain is illustrated by Figure 1.3. Therefore, to review the current literature on NFM, in the context of this thesis, terms may be used interchangeably, based on the language choices by the literature in question, however all will encompass the aims and rationale introduced.

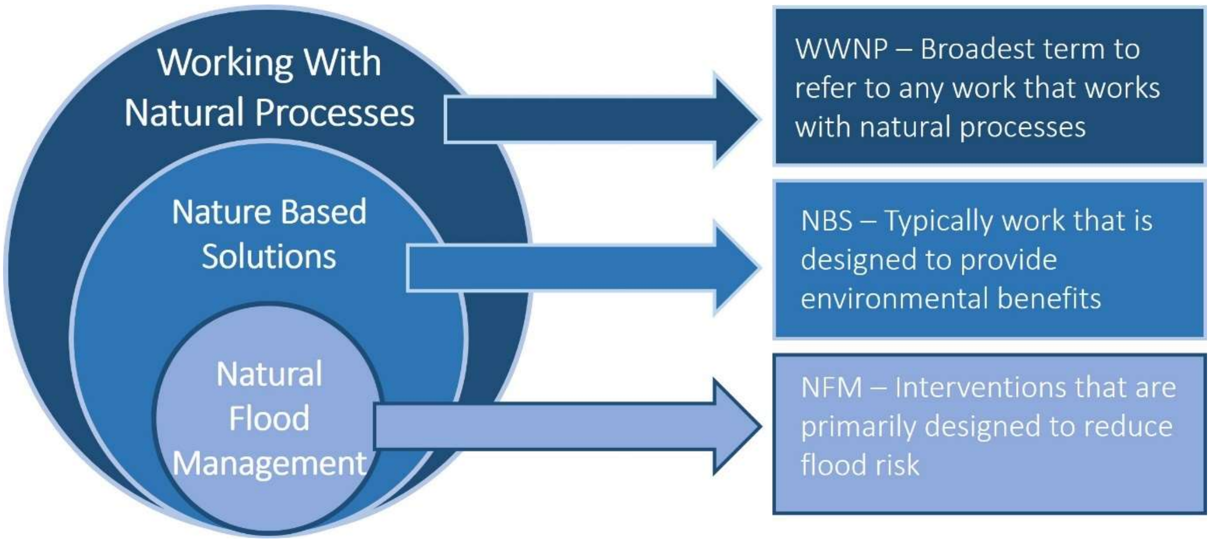


Figure 1.3. Although WWNP, NBS and NFM are often used interchangeably in the literature, this diagram illustrates how these terminologies officially connect. Figure based on diagrams produced by Hollis (2020) and Burgess-Gamble *et al.*, (2018).

1.2.2. Categories of NFM

In recent years there has been a small but growing body of literature that has reviewed the current state of NFM knowledge. These reviews have provided evidence on the general knowledge of NFM features and schemes (Pescott and Wentworth, 2011; Dadson *et al.*, 2017; Ngai *et al.*, 2017; Burgess-Gamble *et al.*, 2018), alongside clear recommendations for future research frameworks (Ellis *et al.*, 2021; Newson *et al.*, 2021). Other reviews have considered a specific NFM type, such as afforestation for flood management (Stratford *et al.*, 2017; Cooper *et al.*, 2021) or leaky woody dams (Gurnell *et al.*, 2019; Lo *et al.*, 2021). Whilst these reviews vary in outlook and focus, collectively they present a strong, wide consensus that an improved and expanded NFM evidence base is required to inform its future role within flood risk management in the UK.

Within recent reviews, NFM measures have been categorised in a number of ways. These include firstly, the WWNP categories: ‘river and floodplain management’, ‘woodland management’, ‘run-off management’ and ‘coast and estuary management’ (Burgess-Gamble *et al.*, 2018). These summarise a range of evidence relating to NFM but within a wider context, for instance including rather than solely focussing on flood risk management. In contrast, a review by Dadson *et al.*, (2017) placed evidence summaries into groups according to flood risk management themes: firstly: ‘water retention through management of infiltration and overland flow’, secondly: ‘managing connectivity and conveyance’ and thirdly, ‘floodplain conveyance and storage’. A more recent review by Ellis *et al.*, (2021) categorises NFM according to key flood risk parameters, to include, roughness, land use, water quality and water quantity. Through a critique of current NFM research, this review makes a number of recommendations for future research including the quantification of plot to catchment-scale mechanisms, consideration of social interactions within NFM structures. In addition, for example the role of flood warden groups and the importance of collecting control datasets for assessing NFM efficacy.

Within these categories, there are a huge range of features, most of which present multiple NFM benefits and are not constrained by a single parameter, group, or theme. Table 1.2 presents a number of the most cited and widely deployed NFM types that have been identified in the literature. This table then matches each NFM type according to a range of parameters, groups or themes that have been used in review studies to categorise these features. This highlights the complex multiple benefits of NFM measures, where all features can be seen to fall into multiple benefits, even within the same review study.

NFM review	Wider parameter, group, or theme	NFM measure							
		Water storage ponds	Leaky woody dams	Beaver dams	In-field barriers/ bunds/	Peat restoration	Grassland management	Woodland planting	Soil management
Ngai *et al.*, (2017)	River and floodplain management	■	■	■					
	Woodland management							■	
	Run-off management				■	■	■		■
Dadson *et al.*, (2017)	Management of infiltration and overland flow						■	■	■
	Managing connectivity and conveyance	■	■	■	■			■	
	Floodplain conveyance and storage	■	■	■					
Ellis *et al.*, (2021)	Roughness		■	■			■	■	
	Land cover						■	■	
	Land use					■	■	■	■
	Connectivity	■			■				
	Water quantity	■					■	■	■
	Water quality	■	■	■	■	■	■	■	■
	Water velocity		■	■	■		■	■	
	Environmental services	■	■	■	■	■	■	■	■
	Economic impacts	■	■	■	■	■	■	■	■
	Cultural impacts	■	■	■		■		■	

	Social impacts	■	■	■	■	■	■	■	■
SEPA, (2015)	Woodland creation							■	
	Land management				■	■	■	■	■
	River and floodplain restoration	■	■	■					
Wentworth, (2011)	Storing water	■	■	■	■	■	■	■	■
	Increasing soil infiltration					■	■	■	■
	Slowing water		■	■	■		■	■	
	Reducing water flow connectivity				■		■	■	
Cook *et al.*, (2016)	Storing water	■							
	Increasing infiltration						■	■	■
	Slowing water		■	■			■	■	
	Reducing hydrological connectivity				■	■	■	■	

Table 1.2. Wider benefits of NFM features, selected based on categorisations of in the literature by SEPA, (2015); Dadson *et al.*, (2017); Ngai *et al.*, (2017); Ellis *et al.*, (2021); Cook *et al.*, (2016) and Pescott and Wentworth, (2011). Shading indicates where NFM feature is expected to impact on a parameter, group, or theme.

Table 1.2 ultimately illustrates the complexities of the mechanisms that are acting behind NFM features and that individual features cannot be entirely constrained by a single parameter as they are largely interacting and one NFM feature typically presents multiple benefits. However, for the purpose of reviews, condensing knowledge according to key themes of interest, such as hydrological processes (eg. reducing hydrological connectivity), flood risk parameters (eg. water quantity), or key aims behind NFM implementation (eg. river and floodplain restoration), can be advantageous. Indeed, this allows for a more concise and clear evaluation of the current knowledge, based on what themes are most relevant or of interest. For example, where some reviews have aimed to present practical guidance and information regarding the delivery of NFM methods, based on the range of techniques available, it is of most benefit to present all NFM features according to their wider measures that are used to produce NFM impacts, such as 'woodland creation' to encompass all types of afforestation (eg. SEPA, 2015). Where reviews have presented methodological frameworks to guide future NFM implementation and impact evaluations, based on key knowledge gaps, it is beneficial to present NFM features according to flood risk parameters (eg. Ellis *et al.*, 2021). Indeed, the separation of NFM according to the mechanisms by which they may be measured in the field (eg. to study their impacts), directly links the key knowledge gaps with the methods that may be needed to fill them.

In light of these ideas, this literature review aims to summarise the current key NFM literature according to key hydrological parameters used by Wentworth (2011) and Cook *et al.*, (2016): attenuation, velocity reduction, runoff control and infiltration increase. These four parameters are all quantifiable measures of water quantity and represent key measurable values by which NFM function and impact can be conceptualised, for instance in terms of timing or volumes. This thesis aims to present and assess the efficacy of a range of NFM measures by quantifying their behaviour and impacts in response to rainfall. This is important to respond to the current call for empirical datasets that quantify hydrological processes and mechanisms (Pescott and Wentworth, 2011; Dadson *et al.*, 2017; Ngai *et al.*, 2017). Therefore, it is important to firstly extract and summarise the current state of NFM knowledge in direct respect to key hydrological processes that are measurable in empirical datasets.

These four hydrological parameters were specifically chosen as they represent four key mechanisms by which water quantities may be altered as a result of NFM. Limiting groups to four allows for a more concise and clear analysis and these mechanisms arguably represent the key primary processes that NFM measure are aiming to alter. In addition, these four parameters may also be further separated into channel-based (attenuation and velocity reduction) and hillslope-based (runoff control and infiltration reduction) features. This allows for a clear understanding where the primary mechanisms are acting in order to generate NFM benefits. Key to NFM is that features are distributed across a catchment in order to respond to flood management from a 'catchment-based approach'. Differentiating between those features that primarily are designed and impact flows on the hillslope (targeting flows before they reach open ditches, streams and rivers) versus those that target flows after they reach the river is useful to separate features according to where they are most likely to be implemented. As introduced, it is important to note that, in reality, NFM features may operate under more than one of these chosen, four parameters, along with other mechanisms (for example as presented in Table 1.2). However, for the purpose of this literature review and to ensure consistency, their primary mechanism, based on the cited literature and functions highlighted there, is presented.

Thus, to conduct this review, the following NFM categories will be examined:

1. Attenuation

Features that are designed to store volumes of water (usually stormwater) in-channel, on the floodplain, or hillslope

2. Velocity reduction

These measures primarily result in the addition of roughness in the channel (or on the floodplain), which cause a reduction in flow velocity.

3. Runoff control

These measures trap and slow runoff (and sediment) on the hillslope or floodplain, targeting runoff before it reaches the river channel.

4. Infiltration increase

These features processes improve soil structure, resulting in increased water storage capacity. This causes a reduction in overland flow and increase in vertical water movement (infiltration).

1.2.3. Quantifying NFM types according to key hydrological parameters

Whilst these four identified NFM types are flow-based (eg. refer to the storage, diversion or slowing of flow), the wider benefits of these features are also acknowledged in the cited literature, for example for erosion control, habitat creation and biodiversity. These types are summarised in Table 1.3, that represents a summary of empirical and modelling-based studies that have assessed the impacts of NFM and are subsequently referred to in the literature review. Whilst the majority of those studies highlighted make direct associations with Natural Flood Management, a number are cited due to their NFM connotations, for example, where studies were published prior to the widespread use of NFM terminology. This table is not presented to be an exhaustive list of all possible measures but are instead the key papers within NFM programmes, predominantly within the UK.

NFM type/ feature		Empirical studies	Modelling studies
Attenuation	Water storage ponds	(Wilkinson *et al.*, 2010b; Nicholson *et al.*, 2012, 2019; Robotham *et al.*, 2021)	(Salazar *et al.*, 2012; Quinn *et al.*, 2013; Javaheri and Babbar-Sebens, 2014; Metcalfe *et al.*, 2018; Hankin *et al.*, 2019; Nicholson *et al.*, 2019)
Velocity reduction	Leaky woody dams	(Short *et al.*, 2019; Black *et al.*, 2021; Deane *et al.*, 2021; Muhawenimana *et al.*, 2021; Müller *et al.*, 2021a, 2021b)(Wenzel *et al.*, 2014)	(Thomas and Nisbet, 2012; Dixon, 2013; Dixon *et al.*, 2016) Odoni and Lane (2010) (Ferguson and Fenner, 2020a)
	Beaver dams	(Nyssen *et al.*, 2013; Puttock *et al.*, 2015, 2017, 2021; Law *et al.*, 2017; Graham *et al.*, 2022)	(Graham *et al.*, 2020)
Runoff control	In-field bunds, filter barriers and silt traps	(Verstraeten and Poesen, 1999; Evrard *et al.*, 2008b; Barber and Quinn, 2012; Adimassu *et al.*, 2014)	(Evrard *et al.*, 2007b)
	Peat restoration	(Shuttleworth *et al.*, 2019)	(Gao *et al.*, 2016, 2017; Goudarzi *et al.*, 2021)

	Grassland management	(Bond *et al.*, 2020, 2021)	
Infiltration increase	Woodland planting	(Antonarakis and Milan, 2020; Black *et al.*, 2021; Murphy *et al.*, 2021; Peskett *et al.*, 2021)	(Salazar *et al.*, 2012; Iacob *et al.*, 2017; Dixon *et al.*, 2019; Short *et al.*, 2019; Ferguson and Fenner, 2020b; Page *et al.*, 2020; Revell *et al.*, 2021)
	Soil management	(Evans *et al.*, 1996; Burgess *et al.*, 2000; Franklin *et al.*, 2007; Truman *et al.*, 2007; Bormann and Klaassen, 2008; Boulal *et al.*, 2011; Deasy *et al.*, 2014; Sone *et al.*, 2019)	

Table 1.3. Summary of current literature identified for context or relevance for Natural Flood Management. NFM types are categorised according to their primary function: attenuation (to increase storage), velocity reduction (increase friction to inhibit flow), runoff control (to reduce hydrological connectivity) and infiltration increase (to increase soil and storage capacity and evapotranspiration). Citations are presented and referred to in the following text.

1.2.4. The use of empirical and modelling approaches to analyse NFM

The use of empirical and modelling methods within the NFM literature are generally somewhat separate, with studies typically adopting one of the two for the principal methods. This section will introduce the current use of empirical versus modelling approaches for NFM assessments in the literature, to draw on the divide in methods applied in the current literature (Table 1.3).

The generation of empirical datasets, through directly monitoring NFM structures, and thus producing real-world datasets for hydrological analysis, offer marked benefits for assessments of the effectiveness of NFM features (Addy and Wilkinson, 2019). Monitoring observed processes does not require assumptions on catchment processes in the same manner that is necessary for modelling applications and thus sometimes may be associated with greater confidence (Stratford *et al.*, 2017; Black *et al.*, 2021). The current lack of NFM empirical datasets has been attributed previously to a limited number of study sites and typically short-term data records (Ngai *et al.*, 2017). Monitoring data associated with NFM projects in the UK is not commonplace; it is estimated that <6% of UK-based NFM projects are monitored, and even many of those may not be widely accessible (Hankin *et al.*, 2017). The limited quantity of robust datasets is important as the generation of observational data is essential to inform, parametrise and calibrate hydrological models, where high resolution datasets can reduce the simplifications applied to hydrological processes (Stratford *et al.*, 2017; Addy and Wilkinson, 2019). The heterogeneity within individual catchments and often uniqueness of NFM structure design means that empirical evidence in one catchment cannot necessarily be applied to all others. Thus, where results may demonstrate the functionality of NFM at one site, the same effects might not occur if similar works are deployed elsewhere (Dadson *et al.*, 2017). However, the expansion of our empirical NFM datasets, and importantly documentation of the catchment and NFM types and characteristics in question will improve the transferability of these information. This will allow for the transfer of data from one catchment to be used to examine potential impacts in multiple catchments that share similar attributes and parameter values. Paramount to the successful and expansive execution of these methods is the production of a range of empirical datasets that can fuel future catchment-scale NFM assessments, for instance based on modelling applications. The current lack of empirical data has meant that current NFM modelling assessments are constrained by a limited quantity of real-world data to apply or resort to using singular or simple values to cover catchment-scale processes (Ngai *et al.*, 2017; Ellis *et al.*, 2021). A small number of studies involve the generation of both empirical and modelling results, by firstly producing empirical datasets that have monitored NFM behaviour, and then utilising this within a modelling application, for instance to consider a larger catchment scale or different quantities of the same feature (eg. Nicholson *et al.*, 2019), however this is not yet commonplace.

Despite the issues surrounding a limited quantity of empirical data for use in modelling applications, modelling studies in the literature that have assessed the effectiveness of NFM features are actually more widespread than empirical studies, where >75% are modelling focussed (Kay *et al.*, 2019). Modelling studies offer the benefit that the costs and feasibility difficulties associated with field research are comparatively minimal. For example, results may be produced sooner if longer term monitoring datasets are not being generated. Moreover, the resources, costs and additional feasibility requirements associated with empirical data collection have meant that the NFM empirical literature largely concentrates on small catchments or reaches for analysis. Modelling studies on the other hand may be able to simulate scenarios or events that have not been captured in monitoring data but that can be conceptualised within a modelling programme (Stratford *et al.*, 2017).

There are therefore marked issues and challenges associated with the gap between modelling and empirical studies within the NFM literature, particularly in regard to their respective benefits and attributes for assessments of NFM. Responses to these issues have started to arise, for example Black *et al.*, (2021) who conducted a 69km^2 catchment empirical study on the impact of a range of NFM features on event peak lag time. This study, for the first time, detected the impacts of NFM features downstream at scales greater than 20km^2, therefore potentially drawing on both key advantages of empirical data collection (eg. real world observations) and the key advantages of modelling studies (the scale at which experiments can be conducted).

In the following sections of this literature review, the current empirical and modelling-based literature will be summarised, focussing separately on four hydrological parameters: attenuation, velocity reduction, runoff control, and infiltration increase.

1.2.5. Attenuation

NFM features that are primarily designed to generate attenuation are typically focussed on the diversion or disconnection, temporary storage and subsequent filtered release of flow (Quinn *et al.*, 2013). Within studies to date, attenuation has been attributed to flood hydrograph lag time increases, particularly during high flow events, causing reductions in event hydrograph peak and overall flood risk reduction (Bullock and Acreman, 2003; De Martino et al. 2012). This is based on the principles that by temporarily storing stormwater in storage areas distributed across a catchment during a rainfall event, for example by diverting and trapping flow on the floodplain, there is consequently a delay to flow reaching downstream, resulting in a smaller and delayed hydrograph peak (Nicholson *et al.*, 2012; Quinn *et al.*, 2013). Attenuation-based NFM structures also present wider benefits, for example habitat creation and nutrient and pollution cycling, along with sediment and carbon storage, and have also been used and applied in wider nature-based solutions (NBS) settings (Morris *et al.*, 2003; Barber and Quinn, 2012; Janes *et al.*, 2017).

Water storage ponds

Water storage ponds represent a more widely applied example of NFM features that primarily are designed to attenuate flow (SEPA, 2015; Ngai *et al.*, 2017; Robotham *et al.*, 2021), see Figure 1.4. for examples. They are frequently depicted within broader 'Runoff Attenuation Features' terminology (eg. Nicholson *et al.*, 2012; Nicholson, 2013; Quinn *et al.*, 2013) and may refer to offline (floodplain) or online (in-channel) storage, along with leaky woody debris (Quinn *et al.*, 2013). Firstly, offline water storage ponds function by diverting water from the main river channel, that is temporarily stored on the floodplain, before being slowly released through an outflow pipe or channel back into the main river (Nicholson *et al.*, 2012). Ponds may be designed using a bund or embankment to retain water or may involve the expansion of existing farm ponds (Davidson, 2014). In contrast, online water storage ponds are connected within a channel or ditch network, therefore having a constant interface with flow. They typically involve the excavation of channel sediment (to enlarge the channel, producing a pond) and constrain flow with an outflow structure. As a result of the use of heavy machinery (eg. for excavation) and use of some hard-engineering materials (eg. PVC pipes for outflows), online water storage ponds are frequently referred to in a hard-engineering context (De Martino *et al.*, 2012; Ngai *et al.*, 2017). In the literature, there is in general a lack of conclusively regarding the role of online ponds in NFM schemes. As a result, features that are established to emulate naturally occurring farm ponds, may be termed 'small reservoirs', even in a catchment based flood management context (eg. Salazar *et al.*, 2012).

Current case studies include work carried out in the Belford catchment, North-East England, where a series of runoff attenuation features were constructed in catchment headwaters, with a key example being offline storage ponds (Wilkinson *et al.*, 2010b). The impact of these ponds for water storage and flood peak reduction was firstly examined by Wilkinson *et al.*, (2010b), who compared water level data and flood peaks in events before and after pond construction. Results indicated marked flow attenuation, where water was stored for up to 8 hours within the attenuation features. This increased the average system peak flow travel time by 15 minutes, relative to peak flow travel times recorded in events before pond construction. Analysis by Nicholson *et al.*, (2019) showed storage ponds to have the largest impact on the rising limb of large magnitude events as storage capacity was reached prior to the event peak. This was highlighted as a particular issue in regard to pond design. In smaller events, peak flow was reduced by 12%, based on mass balance analysis. Further potential issues that may affect the efficacy of attenuation based NFM features were raised by Verstraeten and Poesen (1999) who highlighted the importance of water storage maintenance, specifically in regards for pond sedimentation in their study of retention ponds. Indeed, in their study period, whilst pond capacity for sediment retention remained effective, over time there was an increasing corresponding loss of water retention.

Attenuation-based NFM features have been assessed within modelling frameworks in a small number of studies in recent years, where offline storage ponds have been characterised to consider their impact for flow storage and flood risk. The use of modelling-based methods, as opposed to solely utilising empirical dataset has enabled consideration of different scenarios that haven't been implemented in practice, including altering the number of features within a reach or catchment. This analysis has been key to highlighting in the current literature that the impact of water storage ponds for flood peaks and overall flood risk is not anticipated to be substantial without a considerable total volume of water, for instance through a network of smaller storage ponds or features (Quinn *et al.*, 2013; Metcalfe *et al.*, 2017; Black *et al.*, 2021). Quinn *et al.*, (2013) highlighted that a critical number of ponds was required for effective impacts to be demonstrated, illustrated through modelling applications showing the impact of pond networks, with increasing numbers of pond features (each representing 550m^3 of storage). From this analysis it was noted that until combined pond storages exceeded 10,000m^3, minimal flood peak reductions were reported as the storages had already been filled prior to the event peak due to insufficient capacity (Quinn *et al.*, 2013). This is echoed by Nicholson *et al.*, (2019) where a pond network model was established to demonstrate downstream flow under increasing numbers of storage ponds. This model predicted reduction in flood risk by up to 30%, where 35 ponds were included. Importantly, both of these studies utilised empirical datasets, to underpin their pond network models to consider alternative scenarios (increasing numbers) of interventions (Quinn *et al.*, 2013; Nicholson *et al.*, 2019). This offers a number of advantages for the confidence in these results as the impact of multiple hypothetic features can be investigated, whilst utilising observed river flow data. In addition, by coupling field and modelling methods within one study, there is likely to be a maintained higher understanding of the catchment processes and characteristics as direct observations will have occurred.

Further modelling studies have been used and are developing methods to evaluate the impact of attenuation features on flood peak lag times (Metcalfe *et al.*, 2018; Hankin *et al.*, 2019). The characterisation of NFM storage features and their impact during high magnitude events was conducted by Metcalfe *et al.*, (2018), who demonstrated that the combined impact of a series of NFM storage features could significantly delay event flood peaks. This was importantly deemed to depend considerably on the function of ponds to drain sufficiently following events and thus have adequate storage capacities for subsequent events. To further develop these modelling applications, the importance of gaining additional empirical evidence was stressed, in particular hydrometric data that characterises both pond feature behaviour, upstream controls and downstream impacts (Metcalfe *et al.*, 2018). This may reduce assumptions that are necessary in these and other modelling applications, to achieve efficient representation of storage additions within catchment simulations. For example, a number of studies lump values together (eg. within a singular HRU) to increase efficiency. A key advantage of producing new empirical datasets is that this will enable higher diversities and depths of NFM classifications within future modelling applications.

Due to their constant direct interaction with flow, online storage ponds have often been constructed primarily to trap sediment and manage water pollution. Barber and Quinn, (2012) reported on the impacts of online RAFs in the Belford catchment, where significant quantities of silt were trapped throughout monitoring. This effect was not found to extend to sediment and nutrient trapping during storm events, however. This effect was seen elsewhere, in the Evonlode catchment, Robotham *et al.*, (2021) evaluated the impact of three online storage ponds for sediment and nutrient retention. During smaller recorded events, ponds were found to be able to reduce peak sediment and phosphorus loads, however during the largest recorded events, there was an overall net loss of sediment from the ponds, due to resuspension.

Mechanisms of attenuation as a result of defined water storage ponds are also seen in other features, such as leaky woody dams and beaver dams which can attenuate flow as a result of their morphological impact. These have been widely shown to produce online and offline storage, for example, from pooling behind the in-channel wood and forcing flow storage onto the floodplain. On account of the principal impacts of roughness increase and velocity reduction by which these ponds are formed however, these features are detailed within section 1.2.6 (velocity reduction).

Summary and research gaps

In summary, evidence for the efficacy of offline water storage ponds is currently focussed on a small number of UK catchments. Current results show offline storage ponds can in particular events, attenuate flow, increasing system peak travel time. Pond capacity being reached prior to event peaks is a key limiting factor on storage pond efficacy. This has resulted in recent investigations on the critical number of storage ponds required to produce marked attenuation impacts. However, there is a limited quantity of evidence that has quantified the key impacts of water storage ponds, including their response to rainfall events. In addition, there are minimal applications of the role or effectiveness of online storage ponds within NFM reviews due to a lack of certainty in regard to the border between hard engineered, technical flood management (TFM) and NFM features. Further empirical datasets are required to characterise pond behaviour in different catchments and under different conditions and structural designs.

Figure 1.4. Offline water storage pond, providing floodplain storage during high flow events in the Tone catchment, SW-England.

1.2.6. Velocity reduction

NFM features that operate principally through reducing velocities are largely designed to add roughness to increase friction, both within the channel and on the floodplain, to subsequently slow flow, particularly in times of high rainfall (Thomas and Nisbet, 2007; Pescott and Wentworth, 2011). These features are based on the principles that by enhancing or adding landscape roughness, drag is increased, which increases flow travel time and local water storage upstream and encourages floodplain reconnection, which further exacerbates the effects of friction (Shields and Gippel, 1995; Dixon *et al.*, 2016). These slowing mechanisms are anticipated to delay peak flows downstream in the catchment (Gregory *et al.*, 1985).

Leaky woody dams

Perhaps the most widely applied NFM measure that is seen to primarily reduce velocities as a result of the addition of in-channel roughness are leaky woody dams, see Figure 1.5 for examples (Dixon *et al.*, 2016; Grabowski *et al.*, 2019; Black *et al.*, 2021; Muhawenimana *et al.*, 2021; Müller *et al.*, 2021a). Frequently, the introduction of leaky woody dams within channel reaches are part of wider river restoration projects (eg. Kitts, 2010; Osei *et al.*, 2015; Wohl *et al.*, 2016; Maxwell, 2017; Thompson *et al.*, 2018; Grabowski *et al.*, 2019). Leaky woody dams are designed to emulate naturally occurring in-channel wood accumulations, widely considered a fundamental aspect of natural forested rivers and vital component of a connected, habitat-rich floodplain. Naturally occurring wood has been widely studied and attributed to maintaining a diverse channel morphology, with rich habitats and a river that is well connected to the floodplain (Gurnell *et al.*, 2005; Osei *et al.*, 2015; Martin *et al.*, 2018).

Our understanding of naturally occurring in-channel wood has been fundamental for the design and implementation of artificially deployed leaky woody dams, for example as part of NFM and river restoration projects (Short *et al.*, 2019). In the literature, leaky woody dams are also referred to by a large collection of terminologies, where crossovers are often made between words used to describe naturally occurring wood and words to describe wood that has been artificially introduced, for example, 'Engineered Logjams (ELJs), Large Woody Debris (LWD), wood jams, debris dams and leaky woody barriers (Dixon *et al.*, 2016; Martin *et al.*, 2018; Williams *et al.*, 2020; Deane *et al.*, 2021; Muhawenimana *et al.*, 2021). By introducing large wood or whole trees back across the river channel, a build-up of further sediment and vegetation is expected, further reducing channel efficiency (Deane *et al.*, 2021). Importantly, leaky woody dams should be constructed to allow for baseflow and wildlife (eg. fish) to travel unimpeded underneath the dam (Short *et al.*, 2019). Based on the mechanisms of naturally occurring wood, these velocity reductions in-channel as a result of substantial roughness additions and blockages are expected to force localised water storage both onto the floodplain, and behind the leaky woody dams in pools (Gippel *et al.*, 1996; Kitts, 2010; Grabowski *et al.*, 2019). Design criteria for leaky woody dam deployment has expanded widely in recent years, although there is some variation in recommendations, for instance whether dams should be fixed in place to reduce the chance of dam movement, which could pose risks to blocking key man-made channel features, such as bridges (Deane *et al.*, 2021).

Studies on in-channel wood have largely focussed to date on naturally occurring wood, which has been widely evaluated in the literature and its impacts for factors such as channel morphology, velocity reduction and flood risk widely considered (Gregory *et al.*, 1985; Braudrick and Grant, 2001; Mazzorana *et al.*, 2011; Deonie *et al.*, 2014; Martin *et al.*, 2018; Klaar *et al.*, 2020). Whilst leaky woody dams deployed in rivers by humans are designed to emulate these naturally behaviours, their function and impacts are not expected to be indistinguishable and this is an area of comparatively little research (Muhawenimana *et al.*, 2021). Indeed, wood density, shape and positioning in-channel are going to be different to wood that naturally collects (Ngai *et al.*, 2017). This is also reflected in the distinct differing types of artificially deployed leaky woody dams that exist, which present varying impacts for channel morphology, including storage production (Lo *et al.*, 2021). In addition, whilst naturally occurring wood occurs in response to trees in floodplain woodland falling into the channel or transported in-channel material from further upstream, leaky woody dams are purposefully deployed in chosen locations, for example to target specific local issues.

To provide evidence for the efficacy and use of leaky woody dams for flood risk reduction, a small but rising quantity of studies have examined the impacts of artificially deployed leaky woody dams, with some focussing on wider river restoration projects (eg. Dixon *et al.*, 2016), whilst others with a specific NFM focus (eg. Dodd *et al.*, 2016; Hankin *et al.*, 2020). Leaky woody dam introductions have been attributed to increases in flow travel time on account of in-channel velocity reductions and storage creation (eg. Sear *et al.*, 2010; Deonie *et al.*, 2014;

Dixon *et al.*, 2016). Beaver re-introductions have worked on similar principles, where the building of dams is attributed to increasing channel and floodplain roughness, increasing water depth and thus water surface area from floodplain reconnections and ponding behind dams, where flows take a diverted, slower and rougher path to reach downstream (Puttock *et al.*, 2017, 2021; Brazier *et al.*, 2021; Graham *et al.*, 2022). This storage of water depends up on the available freeboard, for instance where pond storages behind dams are low prior to an event, there is an expected greater capacity for dams to attenuate flow (Graham *et al.*, 2022). These controls are anticipated to be similar for artificially deployed leaky woody dams, including their expected location, where beaver dams are typically located in small, shallow, headwater streams (Graham *et al.*, 2022).

Extensive wider impacts are also clear from in-channel wood accumulations, in terms of their potential ecological benefit. These reported impacts include the creation and diversification of river habitats and food sources (Braccia and Batzer, 2008; Senter and Pasternack, 2011), enhancement of ecosystem functioning (Flores *et al.*, 2011) and increases in biodiversity (Cashman *et al.*, 2016). These wider benefits are often driven from the sedimentation and morphological changes derived from leaky woody dam introduction. Indeed, where leaky woody dams trap sediments, stepped channel cross sections and long stream profiles can be produced, with varying depths and velocities as a result of the formation of pools and riffles (Linstead and Gurnell, 1999; Ryan *et al.*, 2014).

Currently, studies that have assessed the effectiveness of leaky woody dams in a NFM context have most commonly used modelling techniques (eg. Thomas and Nisbet, 2012; Dixon *et al.*, 2016; Metcalfe *et al.*, 2017). These impacts have largely been examined using key hydrological metrics, notably peak travel time, which was highlighted to be reduced as a result of leaky woody dam development, by Kitts, (2010) and Thomas and Nisbet, (2012). Indeed, Kitts (2010) demonstrated a 35 minute travel time increase in a leaky woody dam study reach. In addition, results from Thomas and Nisbet, (2012) showed up to 15 minute travel time increases, which was notably attributed to velocity reductions as a result of increased resistance, causing raised water levels upstream of the deployed dams. Finally, Odoni and Lane (2010) demonstrated a wide range of peak flow reductions, depending on the combination of leaky woody dams included in simulations. Importantly, these results showed that for smaller events, peak flow reductions were found to be markedly lower than for larger events.

Current evidence for the function and effectiveness of leaky woody dams for NFM is highly variable. Firstly, the expected impacts for velocity reduction (for example examined as peak flow delays downstream) are not produced ubiquitously, with both increases and decreases in flow peaks reported. This has been shown in modelling studies, where Dixon et al. (2016) reported downstream flood peak increases and decreases by up to 6% under leaky woody dam scenarios. This was despite also showing overall lengthening of event hydrographs under almost all leaky woody dam simulations. Similarly, overall peak flow reductions were reported in simulations by Dixon, (2013), which also coincided with highly variable overall impacts. In addition, reductions in velocity, producing peak flow delays by up to 15 minutes in high magnitude event simulations by Thomas and Nisbet, (2012), did not relate to any marked flow volume reductions. Confidence in the literature is also limited depending on the robustness of the experimental design used. The use of a control (eg. reach or catchment) or collection baseline data (prior to NFM deployment) is highly advantageous to present a full comparison of observed scenarios with and without NFM (Shuttleworth *et al.*, 2019). For example Black *et al.*, (2021) and Puttock *et al.*, (2021) use a full before-after-control-impact (BACI) experimental framework, which was crucial to enable a full comparison of lags and peak flow changes over time. It is important to note that the cost, risk (eg. chance of NFM deployment does not go ahead) and time associated with deploying baseflow (and indeed, control) monitoring is a key reason why these experimental designs are not fully widespread. In addition, not all study catchments may have a suitable control catchment available and it is important to understand that even those selected will present unknown differences to the main study catchment (Puttock *et al.*, 2021).

A number of studies have used empirical methods to evaluate the wider impact of leaky woody dams, for example for increasing biodiversity (Thompson *et al.*, 2018; Deane *et al.*, 2021; Müller *et al.*, 2021a, 2021b). A small number of these empirical datasets have also detailed the impacts of leaky woody dams for hydrological metrics within a NFM setting, firstly, to reduce stage height by Short *et al.*, (2019), from comparisons of rainfall and river stage values before and after leaky woody dams were implemented. These reductions were attributed to flow resistance causing velocity reduction and the subsequent storage of water. Also stressed in this study was the importance of further empirical data collection to quantify the mechanisms and impacts of leaky woody dams across events and longer periods (Short *et al.*, 2019). Further empirical studies have considered the impact of differing leaky woody dam design for generating backwater effects as a result of localised velocity reduction (Muhawenimana *et al.*, 2021). A catchment-scale empirical approach was taken by Black *et al.*, (2021) and showed marked lag time increases of up to 7.3 hours in smaller catchments where leaky woody dams (in conjunction with other NFM features) had been implemented.

The similarities between artificially deployed leaky woody dams and those created by beavers are widely confirmed in the literature on account firstly of the crossovers in terminologies (eg. Wilkinson *et al.*, 2010a). In addition, in terms of design, both typically consist of large quantities of woody material deployed across the river channel, that has been attributed to reducing velocities in-channel, and as a result attenuating and storing flow in dam pools and by diverting flow onto the floodplain (Hankin *et al.*, 2020; Puttock *et al.*, 2021; Graham *et al.*, 2022). Empirical research into the impact of beaver reintroductions in the UK is ongoing but current results have detailed their impact for reducing peak in-channel flow. For example event peak flows were reduced by up to 66% downstream of beaver dams, relative to upstream in event analysis by (Puttock *et al.*, 2017). Further site and storm analysis demonstrated peak flow reductions across a range of event sizes, including during high magnitude events, when antecedent conditions are high (Puttock *et al.*, 2021). In addition, Graham *et al.*, (2022) highlighted that the highest peak flow attenuation was produced during the largest recorded events on account of the mechanisms of floodplain reconnection, forcing flow horizontally and producing dynamic water stores, also shown by Nyssen *et al.*, (2013).

With regards to the studies referenced here that have considered the impact of leaky woody dams, it is common for analysis to occur in conjunction with floodplain woodland planting (eg. Thomas and Nisbet, 2007; Odoni and Lane, 2010; Dixon *et al.*, 2016, 2019; Ferguson and Fenner, 2020a). This may be largely due to their combined introduction within a study site (eg. as a wider floodplain restoration project), where through afforestation, a future sustainable source of accumulating in-channel wood is secured, thus securing a river 'wood cycle' (Gurnell *et al.*, 2019). The effects of floodplain reconnection; a key aim behind large woody debris deployment, have been found to be markedly amplified when linked with floodplain planting and an increase in floodplain roughness (Thomas and Nisbet, 2007; Metcalfe *et al.*, 2017). However, whilst this enables assessments of the impacts of river restoration projects, of which leaky woody dams are a typical component of, this does add complications when trying to highlight the individual impacts of leaky woody dams and differentiating between their hydrological impacts and that of afforestation. Therefore, the quantification of key hydrological processes in these studies (eg. flow), cannot always be directly attributed to a specific NFM type, and instead may be assigned to the whole system, reach or catchment changes. For the purpose of this literature review, afforestation in a NFM context is considered in section 1.2.8 (infiltration increase) on account of the impacts of tree planting, where root growth promotes the breaking up of soil, improving soil structure that includes greater pore spaces for water storage, enabling a reduction in runoff.

Summary and research gaps

In summary, evidence for the impact of leaky woody dams under NFM is largely based on our understanding of naturally occurring in-channel wood. Studies that have quantified the impact of artificially deployed leaky woody dams under NFM are mostly based on modelling methods and are constrained by a limited quantity of empirical datasets that consider a range of catchment types and event magnitudes. The small quantity of empirical studies that have evaluated the impact of leaky woody dams or beaver dams have highlighted their potential to reduce downstream peaks and increase event lag times. However, importantly these results are often highly variable with most reporting both flow peak increases and decreases, depending on the event in question. Therefore, it is of importance to guide future leaky woody dam design and deployment to produce new empirical datasets that detail the response of newly deployed leaky wood dams to rainfall events and their impact for channel flow.

Figure 1.5. Leaky woody dams, deployed for floodplain reconnection purposes.

1.2.7. Runoff control

Runoff control NFM features can be seen to largely focus on intercepting and trapping surface overland water flows, thus reducing runoff connectivity on the hillslope (Pescott and Wentworth, 2011). These measures target quick flow, by directly capturing and filtering overland flow, where sediment can settle out prior to water output, which reduces their overall immediate input into downslope river systems. For the purpose of this literature, these runoff control features are separated from those that primarily increase infiltration, through improvements to soil structure (see section 1.2.8), although importantly both can be seen as targeting flood management on the hillslopes. These are separated to explicitly examine the key hydrological mechanisms and values that can be extracted from these features, where for runoff control features this principally centres around overland flow or runoff values, measured on the hillslope. In contrast in section 1.2.8, greater emphasis is placed on the impact of features for infiltration values and the values quantifying water movement through the soil, rather than moving across it. Examples of features that can be seen to primarily target runoff control include runoff attenuation ponds (for instance where they are constructed along runoff pathways, differing to offline storage ponds, which directly intercept channel flow), planted buffer strips, sediment traps, filter barriers and in-field bunds (Pescott and Wentworth, 2011; Burgess-Gamble *et al.*, 2018).

Constructed runoff control features

Firstly, the role and impact of constructed runoff control NFM features, such as in-field bunds, filter barriers and silt traps, are often primarily considered for their wider benefits for NFM, including water quality improvements, carbon sequestration and erosion control, see Figure 1.6 for examples (Evrard *et al.*, 2008b; Adimassu *et al.*, 2014; Ngai *et al.*, 2017). Runoff attenuation ponds, also known as retention ponds, have also been studied in the literature for the impacts at trapping water and sediment, with evidence found primarily outside UK catchments. These have been deployed specifically in response to 'muddy floods', where high volumes of generated runoff produce high erosion volumes, that are transported downslope (Evrard *et al.*, 2008a). The potential of retention ponds was documented by Verstraeten and Poesen, (1999), where such features were considered on account of their potential benefits to store and filter overland flow and trap sediment. A series of studies have examined the impact of runoff attenuation bunds, constructed in an overland flow pathway in the Belgian loess belt, targeted in an area previously extensively affected by muddy floods (Evrard *et al.*, 2007a, 2007b, 2008b, 2008a). Through modelling their efficacy during high magnitude events, peak discharge and runoff volume reductions greater than 40% were shown, as a result of interception by the constructed bunds (Evrard *et al.*, 2007b). Through monitoring their impacts, empirical datasets produced by Evrard *et al.*, (2008) found the features to reduce peak overland flow by 69%, where runoff was delayed by up to 12 hours behind the bunds. In addition, large volumes of sediment deposition behind the bunds were found, along with markedly reduced catchment sediment yield. This study also highlighted the potential importance of combining these measures with those that target soil infiltration increase for runoff reduction (see section 1.2.7 (infiltration increase). However, overall, there is little evidence for how constructed runoff control features may reduce flood risk, for instance based on slowing and trapping overland flow. Indeed, the few studies mentioned here represent a very small quantity of catchments. Moreover, these types of features are often very small in design (eg. situated in the corner of fields, in runoff pathways), making the quantification of flow or volume values challenging.

Hillslope vegetation management

Secondly, improvements to hillslope vegetation management have been studied for its effects for NFM (Bond *et al.*, 2020, 2021). These are based on the principles that by increasing surface roughness, overland flow velocities are reduced as runoff is slowed and temporarily trapped on the hillslope. Bond *et al.*, (2020) measured overland flow velocities across various grassland habitats and across seasons, demonstrating significant increases in overland flow velocities where surface roughness was reduced (following grass cutting). This study also highlighted the hazards associated with assuming overland flow values as inputs within modelling frameworks, where comparisons with Darcy-Weisbach roughness estimations found they highly over-estimated velocity values. A similar conclusion was derived from additional measurements by Bond *et al.*, (2021), where grassland habitats with greater surface roughness (not grazed) were found to have longer overland flow durations.

The attributes and impacts of peatlands as an ecosystem service have been widely considered, particularly in recent years in regard to the negative implications of peatland drainage (for example, for burning and to increase agricultural land). The re-establishment of peatland habitats and its restoration is a wider part of previously introduced Nature Based Solutions (NBS), however in recent years has also been studied for its direct impacts for reducing overland flow, even where flood management has not been a primary focus of the initial restoration works (Gao *et al.*, 2016; Goudarzi *et al.*, 2021). This is relatively unusual as for the majority of NFM measures, wider benefits are typically not analysed alongside hydrological parameters to assess flood risk impacts. However this presents marked advantages where a full framework of the ecosystem services that measures can offer can be produced as is of particular importance for future implementation in policy, for instance through new environmental land management schemes (DEFRA, 2021b).

As a result of these coupled studies, evidence has arisen regarding the benefits of peatland restoration for delaying stormflow and reducing peak event discharge (eg. Gao *et al.*, 2016, 2017; Shuttleworth *et al.*, 2019; Goudarzi *et al.*, 2021). The impact of blanket peat restoration on catchment runoff was examined by Shuttleworth *et al.*, (2019), considering both the revegetation of bare peat and gully blocking as two key peat restoration methods. Empirical results showed following revegetation, an increase in overland flow generation, with no change to runoff coefficients. However, also shown were a 106% event lag time increase following revegetation and a 27% reduction in event peak flows. In plots where gully blocking was also included, further increases in lag times and reductions in peak flows were demonstrated. These changes were attributed to the higher water table as a result of restoration, thus generating greater overland flow. Modelling methods were conducted by Goudarzi *et al.*, (2021) to consider how different catchment processes interact to generate these monitored peak flow delays as a result of peatland restoration. Results in this study showed the importance of additional surface roughness as a result of revegetation and gully blocking in reducing overland flow speed and volume.

Summary and research gaps

In summary, the effectiveness of runoff control features are typically assessed for their impact on trapping sediment, as a wider benefit of NFM. A small number of empirical and modelling studies have documented runoff decreases, where bunds have been constructed in overland flow pathways, although this is largely dependent on studies in non-UK catchments. In addition, increasing roughness through improving hillslope vegetation management has also demonstrated marked reductions in overland flow. The potential benefits of peatland for increasing event lag times and decreasing peak flows has presented a relatively recent addition to rationale for peatland restoration. To add this to this knowledge base, further datasets are required that examine the impact of runoff control features across a range of catchment types and importantly, scales.

Figure 1.6. In-field bunds for sediment trapping and filtering, deployed along runoff pathways at two farms in the Tone catchment (SW-England)

1.2.8. Infiltration increase

The fourth group of NFM features are those that primarily aim to increase water infiltration and typically focus on improving soil structure, to increase soil water storage capacity, reducing overland flow and erosion (Pescott and Wentworth, 2011; Cook *et al.*, 2016; Stratford *et al.*, 2017). These are largely encompassed through land use management practices, such as improved soil practices and tree and vegetation planting. Anticipated benefits for NFM as a result of improved land management is based on the principles that by increasing soil infiltration, lower volumes and speeds of overland flow are produced during rainfall events, reducing the overall size of event hydrographs and downstream flow peaks (O'Connell *et al.*, 2007). An improved soil structure is associated with greater soil pore spaces and a greater water transmissivity, allowing for a greater water storage capacity (Douglas *et al.*, 1998; O'Connell *et al.*, 2007; de Almeida *et al.*, 2018). Reducing runoff is also expected to reduce the transportation of sediment and diffuse pollutants overland (Franklin *et al.*, 2007).

Soil management practices

A first key example of where NFM has aimed to increase soil infiltration are soil improvement methods within wider agricultural practices, see Figure 1.7a for an example. These have been considered for their potential to contribute to catchment-wide flood risk reduction if targeted appropriately and effectively (O'Connell *et al.*, 2007; de Almeida *et al.*, 2018). Examples of agricultural methods that are increasingly cited in this area include machinery-based methods for improving soil structure, for example conservation tillage, subsoiling and aeration (Truman *et al.*, 2005; Franklin *et al.*, 2007; Smith, 2012; de Almeida *et al.*, 2018), and the use of cover crops or crop rotation (García-González *et al.*, 2018; Loaiza Puerta *et al.*, 2018). Soil management methods have been frequently and widely applied within agriculture, most commonly for their anticipated benefits to local soil structure and to improve crop yield (Jin *et al.*, 2007; Leskiw *et al.*, 2012). However, their consideration as potential flood management methods is far newer and an area of increasing research in recent years (O'Connell *et al.*, 2007; Deasy *et al.*, 2014; Alaoui *et al.*, 2018).

Subsoiling and aeration practices have demonstrated benefits for reducing compaction, increasing water infiltration, and enhancing soil properties, including soil organic carbon (Sojka *et al.*, 1993; Evans *et al.*, 1996; Zhang *et al.*, 2011; Feng *et al.*, 2018; He *et al.*, 2019b). Through conducting rainfall simulations to assess the impact of reduced and strip tillage as soil management methods for improving infiltration, Laufer *et al.*, (2016) demonstrated runoff reductions of up to 92% at the plot scale. Higher runoff values were also reported by Rhoton, Shipitalo and Lindbo (2002) under control plots, relative to no-till, as a method of soil conservation which was conducted. The use of cover crops to improve soil organic content, structure and hydraulic conductivity was explored by García-González *et al.*, (2018), who demonstrated their benefits for improving infiltration, alongside wider benefits such as erosion reduction and carbon sequestration. Infiltration increases were reported under all scenarios measured, although this notably took many years to show within the produced results. The timescales associated with how long soil management measures are effective for are a key uncertainty in the literature (Curran Cournane *et al.*, 2011; Sone *et al.*, 2019) and is further limited by the typically short time scales for testing or monitoring (Ngai *et al.*, 2017).

Current understanding is based on highly variable data, where the impacts of soil management methods for improving infiltration, as a key component of reducing flood risk, is not always clearcut. The effectiveness of improving water infiltration locally is subject to many factors including catchment characteristics, soil type and depth, the conditions studied, such as the event magnitude and the present soil health and extent of degradation (Evans *et al.*, 1996; Burgess *et al.*, 2000; Franklin *et al.*, 2007; Truman *et al.*, 2007). Thus, these infiltration improvements highlighted in the literature, are not representative of all studied catchments, for example with a number of datasets demonstrating highly variable results, with both increases and decreases in infiltration and downstream flood risk as a result of soil management methods (eg. Smith, 2012; Deasy *et al.*, 2014; Sone *et al.*, 2019). To improve this knowledge base, additional datasets are required that can quantify the processes associated with soil management methods. Then in the future, the collation of this information may take into account the current uncertainties, including catchment size and variability, differences in soil types and depth and the impacts of varying storm events (Boulal *et al.*, 2011; Deasy *et al.*, 2014).

Woodland Planting

A second key, broad area of land management, that has been placed within a NFM context in recent years is that of the role of woodland in regulating and reducing river flows. It is widely accepted and is an area of study and review that far precedes the introductions of NFM terminologies within the literature in recent years (Clark, 1987; Mount *et al.*, 2005; Iacob *et al.*, 2017; Stratford *et al.*, 2017). Therefore, the inclusion of afforestation within NFM schemes in the UK is thus backed on a large volume of historical literature and is based on the key mechanisms by which tree planting is expected to improve infiltration, where root growth breaks up the soil, improves soil structure and increases pore spaces for water storage and vertical movement (Stratford *et al.*, 2017). Tree planting is also attributed to the basic mechanisms of water interception, floodplain stability, as well as the eventual provision of naturally occurring in-channel wood (Gregory *et al.*, 1985; Carroll *et al.*, 2004; Marshall *et al.*, 2009, 2014; Lunka and Patil, 2016), also see section 1.2.5. The wider benefits of woodland planting have been progressively attributed to broader impacts for carbon sequestration (for instance as NrBS strategies), increasing biodiversity, re-naturalising catchments and mitigating pollution (Hess *et al.*, 2010; Wahren *et al.*, 2012).

In a direct response to this scientific backing, woodland planting has been a widely utilised and a key NFM strategy within UK schemes in recent years. This has included numerous forms of afforestation including native and non-native floodplain and hillslope planting, shelter belts and hedges, see Figure 1.7b for an example (Morris *et al.*, 2016; Ngai *et al.*, 2017). The impacts of afforestation, grazing and grassland changes, has been documented by a number of studies (eg. Marshall *et al.*, 2009, 2014; McIntyre *et al.*, 2014; Wynne-Jones, 2016; Revell *et al.*, 2021b). Firstly, the effects of afforested shelterbelts for local surface runoff studied by Marshall et al. (2009) showed a significant increase in saturated hydraulic conductivity in areas with 7-year-old trees in comparison to improved pasture areas. An earlier study by Carroll *et al.*, (2004) showed infiltration rates under tree shelterbelts to be up to 60 times higher than in improved pastures. Marshall *et al.*, (2014) demonstrated further results where afforested plots produced smaller rising limbs and flood peaks, in comparison to controlled plots in selected events, with greater infiltration rates under afforested areas. More recent research has highlighted the role of native woodlands for NFM and a reduction in event peaks and runoff, attributed largely to high infiltration rates (Monger *et al.*, 2021).

Infiltration measurements were taken by Revell *et al.*, (2021) with increasing distance from annual planted woodlands, which were used to simulate varying scenarios of land cover on peak flows. This study highlights an emerging example of where empirical and modelling methods have been used alongside each other to examine the impacts of NFM, where models can be calibrated and validated using observed values to reduce uncertainties and assumptions.

A number of modelling applications have also assessed the impacts of afforestation for NFM, which widely support the notions that tree planting reduces flood peaks. Hillslope-scale modelling conducted by Jackson *et al.*, (2008), also focussing on Pontbren, demonstrated flood peak magnitude reductions by up to 40%, where strategic tree strips were planted, where effects were suggested to extend up to the small catchment scale ($<12km^2$). Peak flood reductions attributed to woodland creation are also demonstrated in modelling studies by Wahren *et al.*, (2009, 2012) and Thomas and Nisbet (2016). HEC-RAS and River2D model results by Thomas and Nisbet, (2007) showed flood peak travel times to be increased by up to 140 minutes in an afforestation floodplain, with modelled velocity reductions of up to 60-70% in the fastest flowing zones.

It is important to note that the impact and interaction of the key hydrological processes that have been widely associated with tree planting are frequently very catchment-specific and there is a limited understanding of how these impacts for flood risk vary depending on scale, land use, soil type, species and under different climate change projections (Wahren *et al.*, 2009; Dittrich *et al.*, 2019). This knowledge gap is partly as a result of the challenges associated with highlighting single factors that increase or decrease flood risk, where it is thus common for studies to consider the impacts of afforestation as a whole, rather than extracting the singular mechanisms, such as infiltration (Wahren *et al.*, 2012). This is particularly evident for current empirical studies, where there is high variability in the impact of tree planting for flood peaks and a lack of quantifiable values that consider the impacts of different parameters for producing this potential effectiveness, such as catchment scale, tree species, forest age and wider management practices (Stratford *et al.*, 2017). Further empirical datasets that consider the influence of these varying factors may help reduce these uncertainties and provide improved validation within hydrological models.

Summary and research gaps

In summary, two clear types of NFM measures that aim to improve infiltration have been considered: afforestation and soil improvement methods. Firstly, afforestation presents perhaps the most cited and historically applied technique for flood risk reduction, where a range of empirical and modelling based studies have presented the potential benefits of tree planting for increasing infiltration and reducing runoff. There is very high variability in current available data in regard to the mechanisms that affect this efficacy, however. Further datasets are required that quantify these processes and the variety of parameters that are currently generating these high uncertainties to improve future modelling applications. Secondly, although historically and widely applied for local compaction issues and to improve crop yields, the potential for soil improvement methods to reduce flood risk is a relatively new application and one that is currently constrained by a lack of quantified empirical datasets. Current evidence can suggest that agricultural methods (eg. conservation tillage, subsoiling, use of cover crops) can produce marked local runoff reductions and improvements to infiltration, although importantly this is dependent on many catchment characteristics.

Figure 1.7. Example of subsoiled soil, as an agricultural improvement practice for the improvement of infiltration (a) and floodplain tree planting for NFM, also deployed for infiltration increase aims, along with floodplain stabilisation (b). Both examples are located in the Tone catchment, SW-England.

1.2.9. Summary

This review has evaluated the current evidence for the function and efficacy of different NFM measures. A particular emphasis has been placed on the role of NFM for flood risk reduction, on account of the anticipated slowing, diverting, storing, and filtering of flow that these features offer. Key uncertainties and variabilities associated with current results, research gaps and consequently areas for further study are highlighted. This review has considered the evidence for four types of NFM, according to their quantifiable hydrological impact: attenuation, velocity reduction, runoff control and infiltration increase. A summary is conceptualised by Figure 1.8.

From this review of current knowledge, there is evidently an increasing range of evidence that highlights the potential benefits and impacts of NFM strategies for flood risk reduction, based on the four key hydrological parameters considered here. This includes evidence that is focussed on the natural processes that are key to NFM measure understanding, for example, using evidence on naturally occurring in-channel wood to detail our conceptualisation on artificially deployed leaky woody dams. This evidence base includes both empirically and modelling based studies, with the latter largely relying on the collection of observational datasets to calibrate and validate simulations.

Whilst knowledge is increasing and improving for all areas of NFM considered in this review, greater certainty and evidence is required to detail the hydrological processes associated with and impacts of these features. Currently, there are considerably more modelling-based than observational evidence in the literature. These modelling applications are constrained by relying on a limited quantity of hydrological data to characterise and compare NFM features and scenarios. Observational datasets provide real-world values, case studies and recommendations that require thorough monitoring campaigns. Moreover, there are large challenges associated with attempts to characterise NFM features where no observational data is available, for example by assuming catchment processes based on national or even international evidence. Therefore, the expansion of datasets in a range of catchment types and scales will increase the pool of evidence that can be used and transferred between catchments with similar characteristics, for example in future modelling simulations.

	Measure	Confidence in evidence
Attenuation	Water storage ponds	Larger-scale traditional engineering ponds impact for flood risk
Velocity reduction	Leaky woody dams Beaver dams	Impact of naturally accumulating in-channel wood
Runoff control	Constructed runoff control features Peatland restoration Hillslope veget-ation management	Wider benefits of peatland restoration Wider benefits of runoff control features, including their effectiveness for trapping sediment
Infiltration increase	Soil management Tree planting	International evidence/data showing potential to improve structure and yields Comparatively higher quantity of evidence for the impacts of trees for flood risk

Key research gaps
Limited quantity of empirical datasets that characterise and assess the impacts of NFM structures, to include: 1. A range of catchment types (based on land use, soil type, scales). 2. The impact of contrasting NFM designs. 3. The response of NFM to a range of rainfall events. 4. The role and impact of NFM structure, management, and maintenance.

Figure 1.8. Summary of key NFM literature and research gaps, according to four key hydrological parameters.

This is of wider importance to drive and provide evidence for (and against) future NFM uptake and engagement, which is currently limited by a lack of knowledge and local confidence. It is important to note that ultimately, considering the highly distributed nature of NFM features across a catchment, stakeholder and landowner cooperation and uptake is essential for efficacy. Empirical datasets and results present the additional advantage that evidence is more likely to be visible and understandable for groups, regardless of their scientific background. For example, the measures being monitored or tested can be visited and the results produced are directly related to real-world, visible events.

The purpose of this thesis in response to these empirical knowledge gaps, is to produce a range of field-based analysis to detail and evaluate the design, function, and effectiveness of NFM features. This will contain a focus on three of the four NFM types highlighted in this literature review: attenuation, velocity reduction and infiltration increase measures. These were selected firstly, based on the deployment of these features within the chosen study catchment (which will be detailed in chapter 2). Secondly, as this thesis will focus on the impacts of NFM for flows and mechanisms to produce quantifiable data to aid future flood risk analysis, the study of NFM measures that primarily operate by altering hydrological processes are of greatest interest. Indeed, runoff control NFM features are found generally to have a greater importance for the wider benefits of NFM, to notably include sediment and pollutant trapping.

In the subsequent results chapters of this thesis, a range of hydrological processes (eg. flow, infiltration) and conditions (eg. range of storm events) will be considered. This is important as a comprehensive evidence base requires the consideration and conceptualisation of key hydrological parameters and inputs to quantify the function and impact of NFM features, and for future validation of these features within hydrological modelling frameworks. These results may be applicable as stand-alone empirical evidence, to highlight the impact of NFM features immediately downstream or within the study area. However, these datasets may be utilised within future modelling applications, to aid the characterisation of NFM features or as observational data.

1.3. Thesis aims, research questions and objectives

In light of the current NFM knowledge base evaluated here and the key research gaps identified, the purpose of this section is to set out the key aims and research questions of this thesis.

1.3.1. Thesis aims

This thesis aims to assess the function and efficacy of Natural Flood Management measures, according to key hydrological parameters: to slow and attenuate flow, reduce runoff, and increase infiltration, with particular consideration to the role and impact of NFM structure design and management. To achieve this aim, key hydrological parameters were monitored and studied at nine NFM sites in Somerset (SW-England) between 2018 and 2020.

1.3.2. Research Question 1: What is the efficacy of offline water storage ponds for attenuation?

There is growing evidence that water storage ponds may be effective for Natural Flood Management on account of their impact for increasing peak travel times and attenuating stormwater. However, this current evidence is based on very few empirical datasets, catchments, and quantity of storm events, which limits the current evidence base as pond function and efficacy is dependent on numerous parameters, including catchment-scale, antecedent conditions, and storage capacity. Notably studies that have examined offline storage ponds to date, have highlighted potential issues in their design and function, including the impacts of pond capacity being reached prior to the event peak.

Therefore, the first research chapter of this thesis: Chapter 3. Assessing the efficacy of offline water storage ponds for Natural Flood Management, examines the efficacy of two contrasting designs of offline water storage ponds for Natural Flood Management. Firstly, a comprehensive event definition methodology is developed and used to evaluate the impact of ponds on downstream flow, based on dynamic storages across rainfall events. In addition, the structural conditions required for ponds to function as design were considered, utilising high-resolution drone Structure from Motion (SfM), and manually surveyed digital elevation models (DEMs). Here, the dynamic capacities and percentages of storage and flow impact were quantified, providing examples and a dataset for future upscaling and modelling applications to determine the impact of these features at the catchment scale. This importantly considers the key criteria required for pond filling, storing, and spilling and the implications of these factors for overall pond attenuation and efficacy. This is important to assess the impact of two contrasting designs of offline water storage ponds for downstream flow reduction. This provides empirical data to demonstrate the volume and percentage impact across rainfall events that small-scale and floodplain based NFM ponds can have for downstream flow.

1.3.3. Research Question 2: What is the impact of leaky woody dams for in-channel velocity and event peak flow reduction?

The inclusion of leaky woody dams has become increasingly widespread in river restoration projects in the UK in recent years. Based on current evidence, there are emerging indications that leaky woody dams can reduce downstream flows, peak flow magnitude and event durations on account of velocity reduction. However, current knowledge largely relies on studies that have assessed naturally occurring in-channel leaky woody dams, rather than artificially deployed wood. Moreover, current evidence for artificially deployed leaky woody dams is largely contained within modelling studies. These have presented a number of advantages for our understanding of leaky woody dams; however, they have also highlighted the need for further empirical datasets, both for local understanding and to drive future modelling applications.

Therefore, the event definition methodology introduced in chapter 2 and applied in chapter 3 for offline storage pond sites, is now employed for a leaky woody dam site. In Chapter 4: Leaky woody dams for in-channel peak flow attenuation and Natural Flood Management, two stretches of leaky woody dams in the Tone catchment, were monitored, both with corresponding upstream controls in the same channel. This was used to evaluate the impact of leaky woody dams on downstream flows, considering the volume and percentage impact across higher-magnitude rainfall events, and in particular the impact on peak flows upstream and downstream of interventions.

1.3.4. Research Question 3: What is the role of online storage ponds for slowing the flow and the implications of outflow management and maintenance for Natural Flood Management?

The indecision associated with the boundary between more engineered and natural forms of flood management has meant that online water storage ponds are largely omitted from the NFM literature, despite their inclusion within NFM schemes across the UK. Online water storage ponds are typically expected to require close management and regular maintenance, presenting additional challenges that are largely unresolved in the NFM literature. There is a lack of case study examples and evidence to understand their impact, to function as designed and to attenuate water volumes across rainfall events.

Therefore, Chapter 5: The function and impact of managed online water storage ponds for slowing the flow examines the role of online storage ponds for NFM. This is assessed by extracting key hydrological metrics that capture the impacts of the ponds for system travel times. These are analysed from separated rainfall events, defined using the event definition methodology outlined in chapter 2, and further applied in chapters 3 and 4. In addition, the impact of outflow management (closure and opening of outflow sluices) is examined, particularly in regard to the impact this has on event storage. A particular emphasis is placed on the applicability and feasibility of site management tasks and the impact of a local flood warden group to sustain NFM function. This chapter also draws on the key uncertainties regarding the boundary between more traditional, hard engineered flood management and Natural Flood Management, along with the role of local community engagement.

1.3.5. Research Question 4: What is the impact of soil improvement agricultural methods for increasing infiltration, reducing runoff and wider Natural Flood Management benefits?

The literature contains a large volume of knowledge on the use of soil management methods to improve soil structure and in particular, in relation to crop yields. Subsoiling is a key machinery-based agricultural method that has been used to improve soil physical properties and reduce compaction. However, the role of subsoiling and other agricultural management methods for Natural Flood Management is a relatively recent introduction. As a result, current evidence relies on assumptions, based on the principles understood from the aims and rationales behind these agricultural methods. For example, an expectation that methods to improve soil structure, that will increase infiltration, will consequently reduce flood risk. Current evidence on the use of soil management practices for flood risk is variable, where future modelling methods require additional empirical datasets where hydrological parameters, including infiltration and overland flow have been measured across different catchments. This will enable the future consideration of the effects of different catchment parameters, such as catchment size and soil type and depth.

Therefore, to contribute to this knowledge base, in Chapter 6: Subsoiling as an agricultural management method for Natural Flood Management, an assessment of the efficacy of subsoiling for NFM is conducted, based on soil management trials at five farms. This builds on the use of subsoiling as a machinery-based agricultural management method but within an NFM context. Comparing trial and control field types, the impacts of subsoiling for physical and hydraulic soil properties were analysed. This included the analysis of single-ring infiltration test data and the application of rainfall simulator experiments to gain runoff, infiltration, and sediment yield values.

2. Study sites and field methods

2.1. Introduction

Chapter 2 outlines the methodology and experimental framework applied to achieve the research aims and objectives defined in chapter 1. This presents both an overview of the methods and study sites used, as well as providing additional information and context relevant to chapters 3-6. Firstly, the study catchments and wider project context are outlined, followed by study site selection and the key monitoring, and testing methods carried out.

2.2. Study catchments and Hills to levels

Following the impacts of the 2013/14 flooding, Natural Flood Management (NFM) measures were established across Somerset, as part of the launch of the 'Hills to levels' project; a partnership between the Farming & Wildlife Advisory Group, South-West (FWAG-SW), several environmental organisations, and Somerset's farmers. These strategies aim to reduce flood risk and erosion, increase floodplain resilience and produce ecological benefits through velocity reduction, soil infiltration improvements, floodplain reconnection and runoff attenuation through a 'catchment-based approach' to flood management (Nicholson *et al.*, 2012; Society, 2018). These NFM schemes have largely been organised opportunistically, meaning site visits, plans, advice and NFM construction have largely occurred in response to landowner engagement and agreement. In addition, local knowledge (eg. from farmers and landowners) was primarily use in the design of individual structures, for example, where on the land they may have the best potential impact of interrupting or attenuating flow. Widespread uptake has meant that Hills to Levels has made notable progress on a farm scale, through soil husbandry advice, water storage construction, afforestation and habitat creation, from which the project has been nationally recognised (FWAG-SW, 2018).

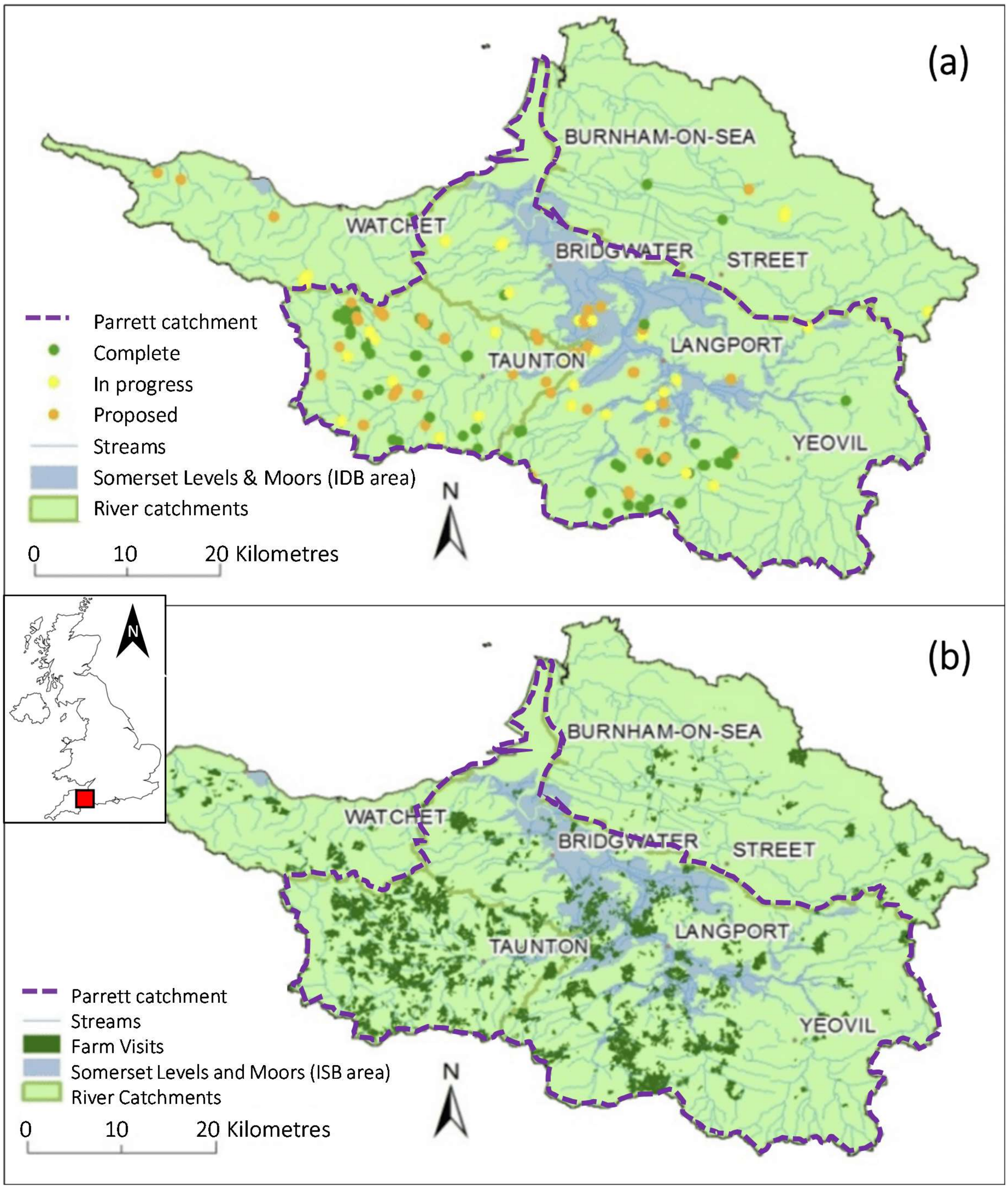
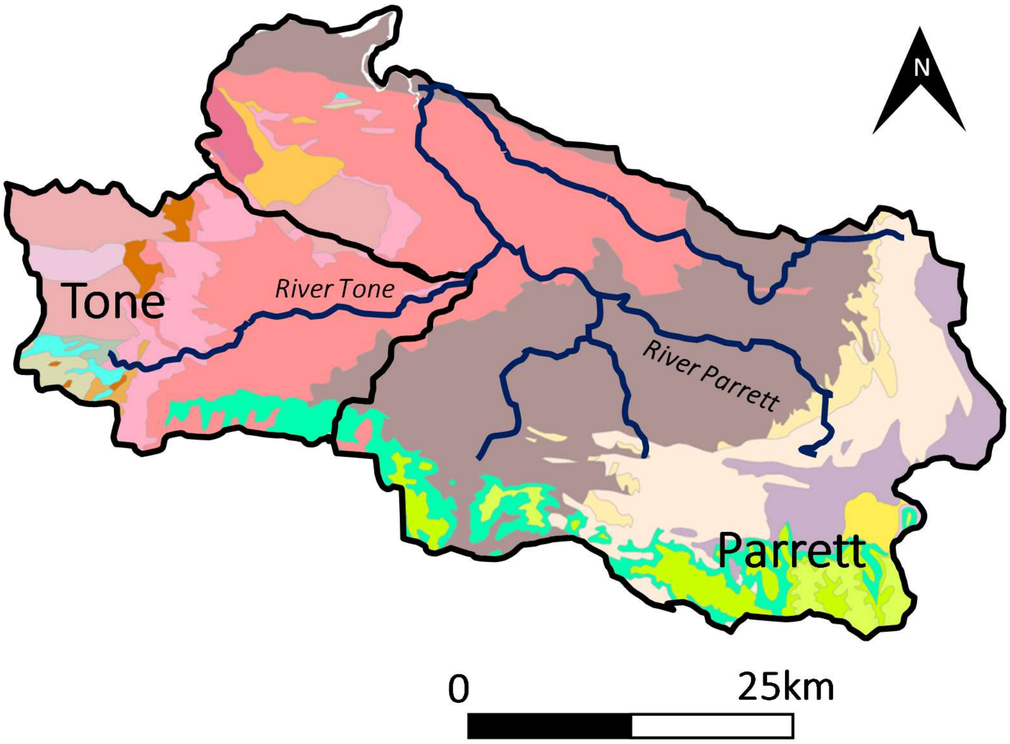


Figure 2.1. NFM delivery under the Hills to Levels project at the time when this project began. Illustrated are the pool of NFM schemes proposed, in progress or complete as part of Hills to Levels (a) and advisory farm visits under Hills to Levels conducted (b). Both maps reproduced from FWAG-SW (2021), with additional Parrett catchment outline indicated. Insert shows catchment location within the UK.

These NFM schemes are largely located across the Tone and Parrett catchments in Somerset, SW-England (Figure 2.1). The river Tone, covers a catchment of $414km^2$, originates in the Brendon hills, draining the Exmoor, Quantock and Blackdown hills. Elevation in the Tone catchment reaches 375m at its source in the Brendon Hills, at Beverton Pond and is underlain by predominantly slate bedrock geology (Figure 2.2). The Tone flows east through Taunton, where bedrock is dominated by sandstone, breccia, mudstone, and conglomerate. The Tone joins the river Parrett ($1700km^2$ catchment area) at Burrowbridge, which is underlaid by mudstone and halite-stone bedrock. The Parrett catchment is tidal for up to 30km from the Bristol Channel, where large areas of the Somerset Levels are only marginally above sea level (Environment Agency, 2009). Elevation in the Parrett catchment reaches 172m at its source near Chedington, which is underlain by mudstone bedrock geology (Figure 2.2). Surface soil percentage silt sand and clay for the Tone and Parrett catchments are shown by Figure 2.3, illustrating the overall low sand proportions across the two catchments, although markedly ranging between 0% and 97%. Silt proportions are generally illustrated to be higher (up to 69%), particularly in the southern Parrett catchment and there are also higher clay proportions (up to 65%), particularly in the northern Parrett catchment.

Across Somerset, maximum temperatures for July (averaged 1971-2000) reach >20ºC, which are shown to be marginally higher (>21ºC) further south in Somerset (see Met Office, 2013). Minimum temperatures for January (averaged 1971-2000) fall to <2ºC. Annual rainfall (averaged from 1971-2000) varies across Somerset, ranging from <800mm further south, to >1300mm further west (see Met Office (2013) for South West England climate summaries). Across the Tone and Parrett catchments, land use is largely dominated by woodland, permanent pasture, grazing, and arable throughout.



Mudstone, Siltstone and Sandstone (MDSS) (Mid – late Jurassic

Mudstone, Siltstone and Sandstone (MDSS) (Mid Devonian)

Sandstone, Limestone and Argillaceous rocks (SLAR) (Mid Jurassic)

Limestone, Sandstone, Siltstone and Mudstone (LSSM) (Mid Jurassic)

Chalk (Late Cretaceous)

Mudstone, Sandstone and Limestone (MDSL) (Cretaceous)

Sandstone and Conglomerate, Interbedded (SCON) (Permian)

Sandstone and Conglomerate, Interbedded (SCON) (Late Devonian)

Chalk (Late Cretaceous)

Limestone, Sandstone, Siltstone and Mudstone (LSSM) (Late Jurassic)

Mudstone, Siltstone and Sandstone (MDSS) (Late Devonian)

Sandstone and Conglomerate, Interbedded (SCON) (Middle Devonian)

Mudstone, Siltstone and Sandstone (MDSS) (Namurian – Westphalian)

Mudstone, Siltstone and Sandstone (MDSS) (Late Devonian – Namurian)

Mudstone, Siltstone, Limestone and Sandstone (MSLS) (Late Triassic – Mid Jurassic)

Figure 2.2. Bedrock geology of the Tone and Parrett catchments (1:25000 Geology, DiGMapGB-250 Rock Units)

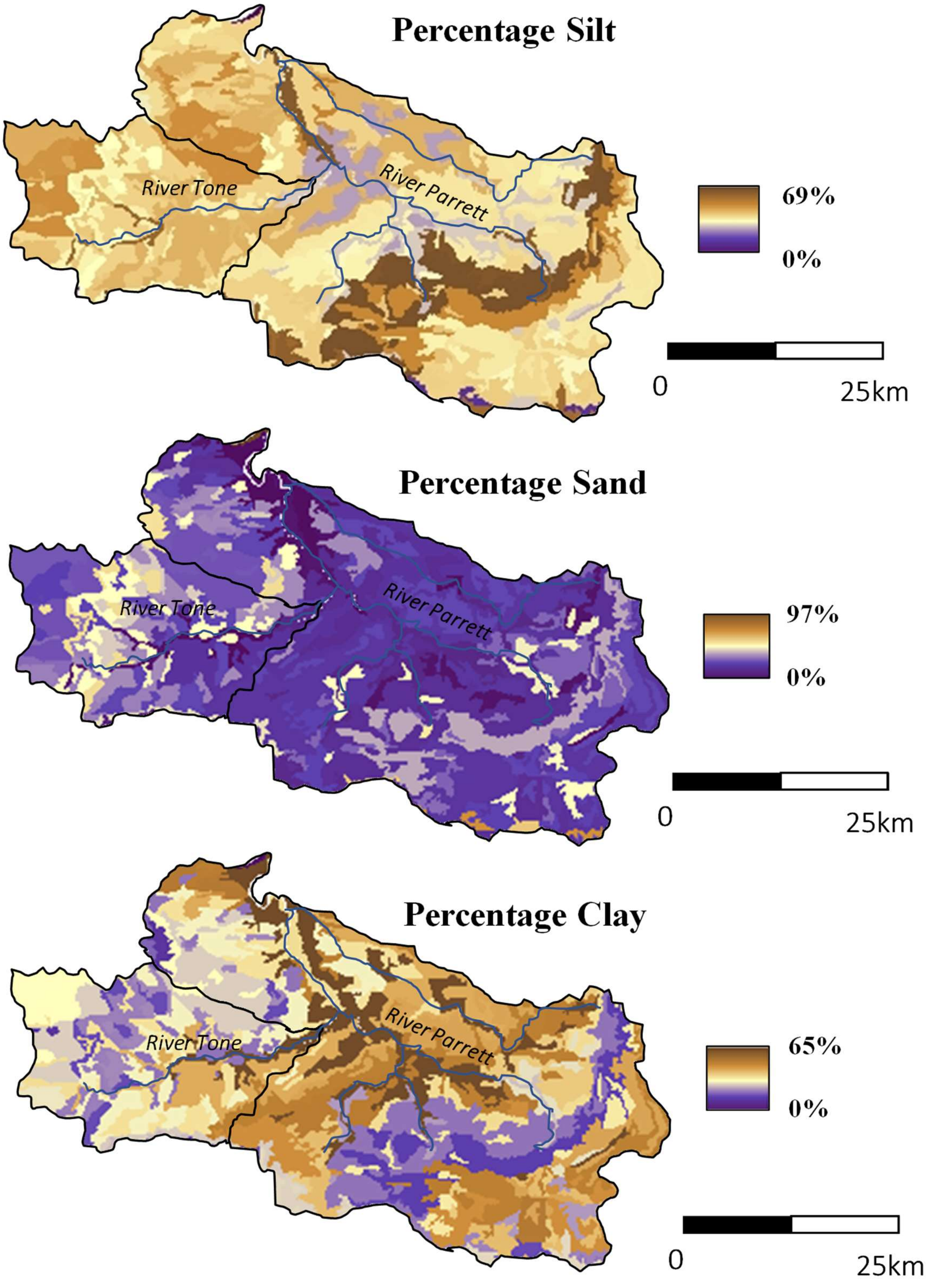


Figure 2.3. Surface soil percentage silt sand and clay for the Tone and Parrett catchments. Raw vector datasets accessed from LandIS National Soil Map of England and Wales (NATMAP). Raw datasets were processed and converted to a 50m raster for Great Britain by Lane (2020). Parrett catchment area was clipped as the area of interest in this thesis.

2.3. Study site selection

To achieve the research questions and objectives set out in chapter 1, the assessment of a range of NFM types was required. Nine sites were selected for monitoring from a spectrum of NFM measures created through Hills to levels across Somerset (see Table 2.1 and Figure 2.4). These nine sites were chosen from a carefully selected series of criteria to ensure their suitability for monitoring, testing and analysis. Table 2.1 categorises these NFM types according to four key objectives: to increase storage, increase friction, reduce hydrological connectivity, and increase soil storage capacity.

Target	River Channel		Hillslope	
NFM type	Attenuation	Velocity reduction	Runoff control	Soil storage capacity increase
Aim	Increase storage	Increase friction to inhibit flow	Reduce hydrological connectivity	Increase soil storage capacity and evapotranspiration
Examples deployed in Somerset through Hills to levels	Connecting floodplains (**offline water storage ponds**). Leaky runoff ponds Leaky outlets (**online water storage ponds**)	**Leaky woody dams**	In-field bunds Cross drains Silt traps Filter barriers Cross-slope hedges Woody flow spreaders	Woodland planting, soil management measures, including over crops and **machinery-based (eg. subsoiling)**
Study site names	Halsewater Merriott Wellhams	Upper Marcombe Lake Lower Marcombe Lake	No sites monitored	Newcotts Frys Wellington Tainfield Staddons

Table 2.1. Categorisation of NFM deployed through Hills to Levels. The examples of NFM deployed in Somerset are based on the techniques and advice available through FWAG-SW, (2017). Those selected to monitor in this project are highlighted in bold. NFM terminology used here match those documented by FWAG-SW, although in the wider literature NFM names vary (eg. for leaky woody dams, names include large wood, wood barriers etc.).

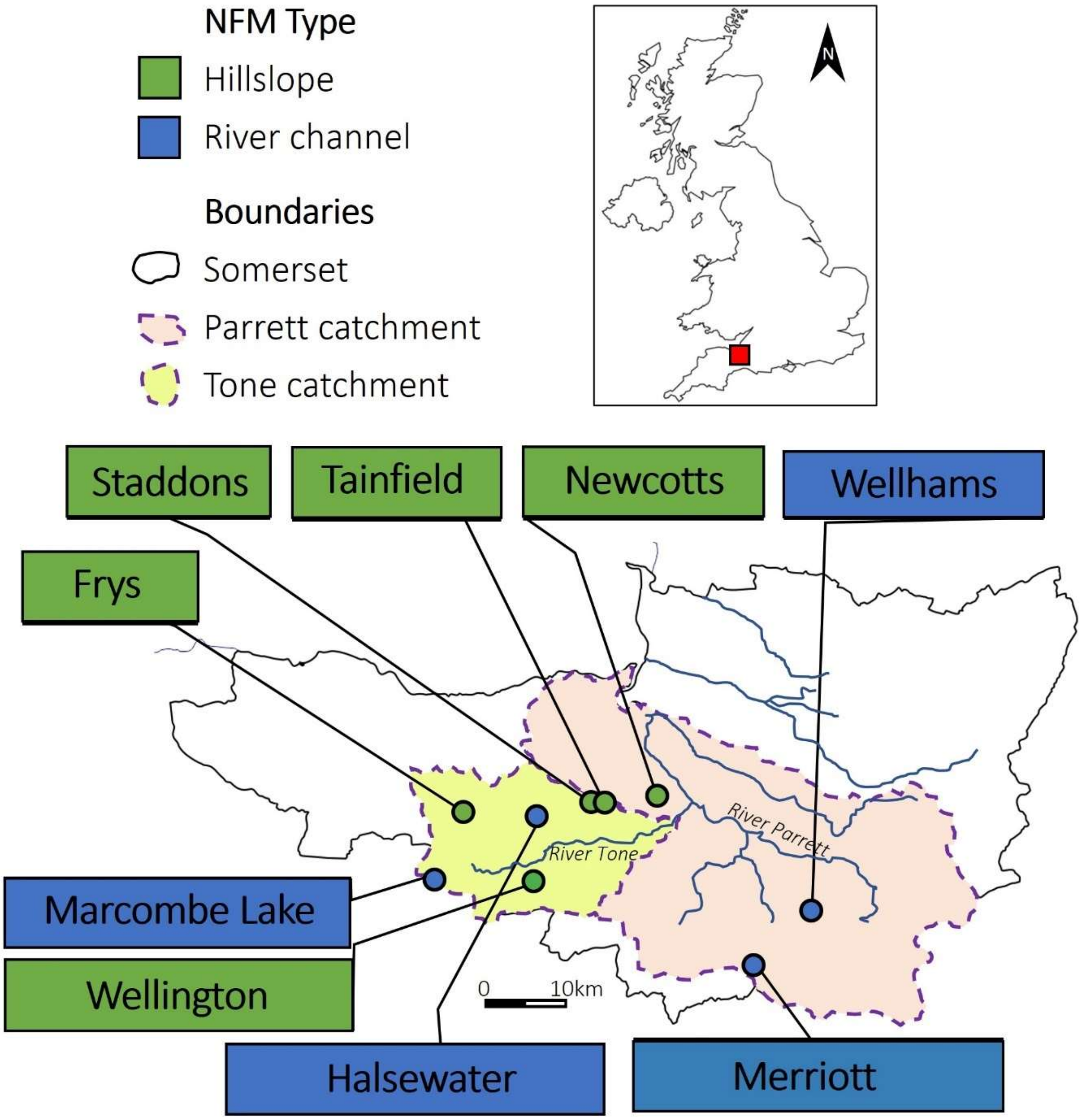


Figure 2.4. All river channel and hillslope NFM study sites, where monitoring and testing occurred between 2018 and 2020. Located in the Tone and Parrett catchments, Somerset.

Potential NFM monitoring sites were divided into 'river channel' and 'hillslope' NFM features (see Table 2.1). Firstly, river channel NFM types are principally designed to store and slow flow by directly impacting river flows, for example by increasing friction in-channel or capturing and storing flow on the floodplain. In contrast, 'Hillslope' NFM types are typically designed to slow flow prior to water reaching the river channel for example by inhibiting runoff pathways on the hillslopes or increasing interception and infiltration of runoff or rainfall. It was decided that a range of 'structural' NFM features that stored or slowed water would be monitored ('river channel' NFM), alongside the study of soil management trials ('hillslope' NFM types), also through Hills to Levels. To ensure the feasibility of monitoring different sites and structures, a series of criteria were considered for site selection. Selection was made following field visits, where the practicality and potential benefits of monitoring were assessed (see Figure 2.5).

For all NFM features ('river channel' and 'hillslope'), the following selection criteria were considered:

a. Sites should be deemed feasible to collect results within a 2-year timescale
b. Sites should be available for the expected monitoring period (eg. established or certain for construction/management).
c. Monitoring and testing must be feasible, for example, channel accessible or access across and within crop.

Some types of NFM were deemed infeasible to monitor in the given timescale of a PhD due to the anticipated slow changes that would be expected. For example, afforestation sites were discounted for analysis as recordable hydrological changes would be unlikely for many years until tree growth. Although hillslope and floodplain tree planting has occurred through Hills to Levels, the timescale since planting (since 2015) would have meant that monitoring would have relied on <2 years of growth (criteria a).

In addition, the potential for baseline monitoring was explored as Hills to Levels schemes are ongoing with various schemes in proposal stages during site selection. The use of baseline data would have been advantageous to develop datasets that characterised these structures before and after installation. However, ultimately, this was deemed infeasible for this project due to the high uncertainty associated with structure construction following an assumed baseline period of monitoring (for example, in-channel prior to floodplain or channel alterations). It was typical for the finalisation of a NFM site to only occur a month before construction and often under a finite budget time-window (criteria b). Furthermore, considering the practicalities of fieldwork, testing and monitoring had to be deemed feasible. For example, the river channel had to be accessible for hydrological monitoring with access by wading and from the bank and for monitoring installations. Also, the site itself had to be accessible without disrupting the landcover (eg. crops) to negate any negative environmental impacts from monitoring or testing (criteria c).

For 'river channel' features, the following additional selection criteria were also considered:

d. Sites should have contrasting designs and functions within NFM
e. Sites should be of sufficient size and scope for water level monitoring to be feasible and quantifiable

To achieve these 'river channel' feature criteria, offline water storage ponds, online water storage ponds and leaky woody dams were selected to consider a range of structures that aim to attenuate and slow flow (criteria d). This is important to gain a range of datasets and analysis to capture the range of NFM deployed throughout Somerset, rather than concentrate on one type. This also allows further inter-site comparisons and a detailed discussion on the suitability of NFM design and function.

To ensure that the response of NFM to rainfall events would be quantifiable, very small-scale features were not considered as it was anticipated that any flows travelling through or stored in them would be minimal. As only small number of NFM structures could be monitored in this project due to time and budgetary constraints, this also maintained a focus on features that were expected to make an impact on channel and flood-peak responses, as opposed to sediment and erosion issues. In-field bunds are an example of these small-scale features, which although have been widely implemented across the Hills to Levels project, are generally installed at a local, field scale, where individual changes to water levels would unlikely be recordable (criteria e).

Given these considerations, two contrasting offline water storage pond sites were chosen: Halsewater and Merriott, along with an online water storage ponds site (with leaky outlet): Wellhams and two sections of leaky woody dams: Marcombe Lake (see Figure 2.4). These sites encompassed a range of larger-scale features established in Somerset and enabled comparison of key floodplain storage designs. In terms of offline water storage pond designs established in Somerset, the features chosen were the only sites (out of those deployed to date through Hills to Levels) that met all stated criteria (a-e). Whilst a number of leaky woody dam sites had been created since 2016 in the Tone and Parrett catchments, Marcombe Lake was selected on account of its potential to offer two sets of control and leaky woody dam channel stretches for analysis, allowing a concentrated experimental design to be developed. Finally, the online storage pond site was chosen based on its unique attributes as a NFM site, such as its management by a local flood warden group and the crossovers between more technical flood management (TFM) and NFM in terms of its construction and environmental focus.

Figure 2.5. Field visits in the Tone catchment, showing first Halsewater visit (later chosen for monitoring) (a), leaky woody dam site not selected due to complex upstream catchment (b).

For soil management trials ('hillslope' features), the following additional selection criteria were considered:

f. Sites should have a control and managed area for comparisons, which must be confirmed by the landowner.
g. These control and trial areas should be of sufficient size for testing to occur where inter-field variation can be considered.
h. Control areas must have been treated 'as usual', for example with ploughing methods used in previous years. Equally, trial (managed) areas must be comparable between sites, for example using similar soil management methods, equipment, and outlook (using standard practices).

To achieve these 'hillslope' NFM feature criteria, five soil trial sites: Newcotts, Frys, Wellington, Tainfield and Staddons, were selected and studied over 3 field seasons (see Figure 2.6). These were subsoiling trials, which used machinery-based soil management methods, aiming to improve soil health, structure, and crop yields. These were largely selected opportunistically, based on the occurrence of field trials in the Tone and Parrett catchments, landowner contacts and agreements. However, they were also needed to meet the stated criteria (criteria a-c, and f-h). Firstly, knowledge was provided by FWAG-SW, through landowner contacts regarding the occurrence of subsoiling trials. Farm visits were conducted to secure provisional fieldwork permissions and ensure the locations and boundaries of control and management field areas could be verified, for example see Figure 2.6b (criteria f). These were typically marked out on field boundary maps and at the sites with markers.

In addition, these trial and control field areas had to be of sufficient size for testing to occur (criteria g). Trials where half of the field had been subsoiled, and the other half used as a control were most ideal for this. In some site visits, we noted that subsoiling was conducted on targeted areas of the field, for example to address specific compaction issues on the headlands of fields. Although this is a common application of subsoiling by landowners (external to NFM schemes and aims), for the purpose of this study, using these sites would have introduced additional variables that would have been complex to differentiate (such as comparing targeted versus untargeted subsoiling). Utilising the whole field for control versus trial transects whilst testing reduces bias and produces results that consider field-wide variation.

Finally, during site visits, subsoiling trials were selected for analysis on account of the comparable methods used between sites, farmers, and landowners. These all utilised subsoilers, which were used to an approximately 30cm depth on the field. The control field area had to be managed ‘as usual’ by the farmer, which typically involved ‘conventional’ ploughing methods: cutting and rotating of the soil, following crop harvest (criteria h). Other inter-site factors such as the time of year of subsoiling, crop type and soil type were not kept controlled between sites and were instead factored in for analysis. This was both a feasibility factor (finding five sites with perfectly matching characteristics, crops and management methods would be impractical), but also provided further points for comparison and discussion.

Figure 2.6. Site visits to select third soil site. Images show Wellington site visit (selected for testing) (a) and a further Tone catchment trial site not selected for testing due to lack of confirmation on the boundary between trial and control sections (b).

2.4. River channel NFM study sites

Firstly, the four river channel NFM sites will be introduced, which were monitored in the Tone and Parrett catchment headwaters. These sites are summarised in Table 2.2.

Site	Catchment	NFM structure	Gauge installations	Time step	Rainfall data	Monitoring period	Chap-ter
Halsewater	Halse Water, Tone catchment	Two floodplain storage ponds with inlet channels and outlet tunnels	4 gauges: In-channel (upstream/ downstream), in-pond (up/downstream)	1 min	Tipping bucket	April 2018 – Dec-ember 2020	3
Merriott	Merriott Stream, Parrett catchment	Two floodplain storage ponds with inlet and outflow channels	4 gauges: In-channel (upstream/ downstream), in-pond (up/ downstream)	1 min	Tipping bucket	November 2018 – December 2020	3
Marcombe	Marcombe Lake, Tone catchment	Two sections of in-channel leaky woody dams.	4 gauges: in-channel	1 min	Tipping bucket - EA Gauge (id. 45168)	December 2018 – December 2020	4
Wellhams	Wellham's Brook, Parrett catchment	Two online ponds	2 gauges: In-channel (upstream/ downstream pond)	1 min	Tipping bucket	November 2018 – December 2020	5

Table 2.2. Key study site and installation details for all 4 river channel study sites. Chapter refers to where the data and analysis for each study site is found within this thesis.

Next, the four chosen river channel NFM study sites are introduced, with an outline for each site and the installations. Greater detail is provided within the respective results chapters.

2.4.1. Halsewater

Halsewater consists of two storage ponds on a shallow-sloped floodplain, with inlet channels and outflow pipes leading from the two bunds into the shallow stream, constructed in 2016. Water level gauges were installed in-channel upstream and downstream and within each pond, with the most upstream gauge at 51.03 -3.21 (WGS-84). Gauge locations and setup are illustrated by Figure 2.7. The ponds were located within a fallow grass field, with the surrounding area being predominantly arable agriculture. The channel has a relatively shallow baseline level, with a deeper, narrower cross-section at the downstream gauge. The analysis of the Halsewater offline water storage ponds can be found in Chapter 3 along with a full site characterisation.

Figure 2.7. Images showing Halsewater site gauge locations: upstream channel (a), downstream channel (b), upstream pond (c) and downstream pond (d).

2.4.2. Merriott

Merriott consists of two floodplain storage ponds, constructed using two bunds adjacent to the river with inflow and outflow channels leading to and from the main channel at the bottom of a valley, constructed in 2016 (Figure 2.8). Water level gauges are installed upstream (Figure 2.8a) and downstream (Figure 2.8b) of both ponds and in the upstream pond (Figure 2.8c), with the upstream gauge at 50.897, -2.801 (WGS-84), downstream of Crewkerne. The channel feeds downstream into the main Parrett River, downstream of Merriott. Monitoring has also taken place by FWAG-SW in the downstream pond and outflow channels. The analysis of the Merriott offline water storage ponds can be found in Chapter 3 along with a full site characterisation.

Figure 2.8. Images of Merriott gauge installations: upstream channel gauge (a), downstream channel gauge (b), upstream pond gauge (c) and downstream pond gauge (d).

2.4.3. Marcombe Lake

Marcombe Lake consists of two study sections: ‘Upper Marcombe Lake’ and ‘Lower Marcombe Lake’. These both include a section of Leaky woody dams and a control section. Upper Marcombe Lake was installed in November 2018, with 8 debris dams, whilst Lower Marcombe Lake was installed in January 2018, with 5 debris dams. Water level gauges were installed, upstream of Upper Marcombe Lake leaky woody dams (Gauge 1, Figure 2.9b), downstream of Upper Marcombe lake leaky woody dams (Gauge 2, Figure 2.9c), upstream of Lower Marcombe Lake leaky woody dams (Gauge 3, Figure 2.9d) and downstream Lower Marcombe Lake leaky woody dams (Gauge 4, Figure 2.9e). The most upstream gauge was installed at 50.977, -3.372 (WGS-84), downstream of Staple Cross. The channel feeds downstream into the main Tone River, north of Wellington. The analysis of the Marcombe Lake leaky woody dams can be found in Chapter 4 along with a full site characterisation.

Figure 2.9. Images showing Marcombe Lake gauge locations for Upper Marcombe Lake: Gauge 1 (a) and Gauge 2 (b); and Lower Marcombe Lake: Gauge 3 (c) and Gauge 4 (d).

2.4.4. Wellhams

Wellhams includes two online ponds, dug out from within the channel and separated between a small section of channel (Figure 2.10a and c), constructed in 2017. These are controlled by two outflow structures (Figure 2.10b and d), managed by a flood warden team. The outflows may be opened or closed and have an overflow gap. By controlling this, the levels of the ponds may be altered according to the season. Close attention to weather forecasts and radar information also occurs, where the outflow may be opened to release water prior to a rainfall event. Given the mechanics of the outflow structures, regular maintenance has been required, for example the removal of debris blocking the mechanism. Water level gauges were installed in each of the in-channel ponds, with the most upstream gauge at 50.947, -2.698 (WGS-84). The site is located downstream of Odcombe, along Wellham's Brook and meets the downstream Parrett main channel downstream of Martock. The site is located within a fruit orchard, and more widely, arable agriculture. The analysis of the Wellhams offline water storage ponds can be found in Chapter 5 along with a full site characterisation.

Figure 2.10. Images showing Wellhams gauge locations and managed outflows: upstream pond gauge (a) and outflow (b), downstream pond gauge (c) and outflow (d).

2.5. River channel NFM study site methods

The following section will detail the key methods conducted at the river channel NFM study sites in this thesis, from installations, through to analysis. Firstly, the water level and rainfall monitoring installations are detailed, presenting the broad methods used across all sites and further referred to with site-specific details in chapters 3-5. Secondly, the key methods for Structure from Motion (SfM) drone flights and manual methods for the production of water storage pond digital elevation models (DEM). These methods are specific to chapters 3 (offline storage ponds) and chapter 5 (online storage ponds), where they are expanded upon. Thirdly, the methods used for channel and pond stage conversions to flow, and storage are detailed. Flow conversions are specific to chapter 4 and 5, whilst volume conversions are specific to chapters 3-5. Finally, details are provided for the key rainfall event definition methodology utilised in chapters 3-6. Methodologies specific to certain sites within chapters 3-5 are detailed within their respective chapter, whilst the information presented here is broadly relevant to all 3 river channel research chapters (chapters 3-5).

2.5.1. Water level and rainfall monitoring

Hydrological monitoring equipment was installed at all sites to quantify the impacts of each NFM structure on system storage and flow (see Figure 2.11). Water level was recorded using HOBO U20L loggers, which were suspended just above the river or pond bed, from a metal slotted angle secured to the ground and within a stilling well, consisting of a drilled PVC pipe (see Figure 2.12 for logger installation setup schematic). Reference readings were taken upon installation and before/after each data download, which typically occurred once a month for Halsewater, Merriott and Wellhams. As the loggers were set on a higher timestep for Marcombe Lake, downloads were required twice a month. Loggers were installed in-channel in a straight section of channel where possible, at the side of the river to avoid the creation of blockages. Whilst all attempts were made to keep the channel as natural as possible throughout monitoring, stilling wells at Merriott did silt up over time and so typically had to be cleared after each download. At Halsewater, the downstream logger had to be removed for a month period for farmer hedge access, a reference stake was kept in the channel throughout to ensure re-installation was as close to the original installation as possible.

Figure 2.11. River channel NFM site field installations. Deploying water level loggers in-pond at Halsewater in April 2018 (a), in-channel at Merriott in November 2018 (b), in-pond at Wellhams in November 2018, where an access platform was added (c) and in-channel at Marcombe Lake in December 2018 (d).

HOBO RG3-M tipping bucket rain gauges were installed at Halsewater and Merriott. Rain gauge deployment can occur either through surface mounting (rain gauge on ground) or pole mounting. To reduce any land damage and for ease of installation, the latter was selected for installations. Rain gauges were attached to a wooden pole, approximately 1m high off the ground, on an area clear from any trees. Whilst these were calibrated prior to deployment, in-field calibrations were conducted annually across the monitoring period to ensure rainfall quantities (2mm/tip) were still accurate. Rain gauges were calibrated with a known quantity of water (373ml), with a flow rate of <20mm/hour. A plastic container with a pinhole on the bottom was positioned on top of the rain gauge to generate this low flow. Once the water volume had passed through the rain gauge, the data was downloaded and checked to ensure it matched the number of tips (1 tip should equal 2mm, thus successful field calibration should result in 100 tips). As Marcombe Lake was located very close to an EA rain gauge (<1km), rainfall data was accessed from here for this site. This dataset was automatically downloaded once a day, via the EA Rainfall API. Due to the close proximity of Wellhams to Merriott, the same rain gauge was used for both sites (deployed at Wellhams).

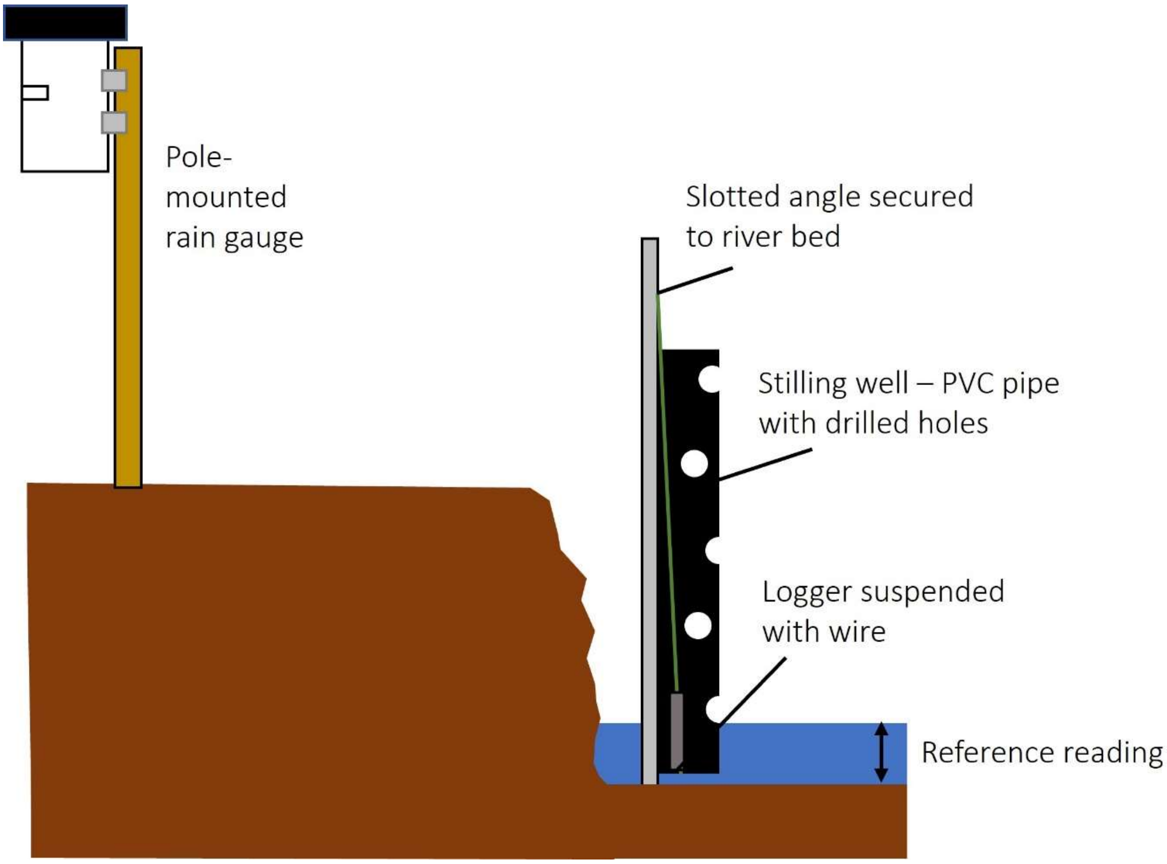


Figure 2.12. Schematic of water level logger and stilling well installation in-channel, along with pole mounting of tipping bucket rain gauge.

2.5.2. Structure from Motion (SfM) for site surveying and DEM production

The use of drones for SfM imagery data collection and production of topographic data has grown extensively in recent years on account of their increasing ease of operation, repeatability and automation through pre-programmed flights, lowering costs, rising availability and high potential spatial coverage (Tonkin *et al.*, 2014; Smith *et al.*, 2015; Anderson *et al.*, 2019). Drone SfM has been increasingly recognised as a method for producing high resolution digital elevation models (DEMs), from which landscape and feature scale measurement extraction can occur (eg. Fonstad et al. 2013; Marteau et al. 2017; Ouédraogo et al. 2014; Westoby et al. 2012).

SfM from a drone platform was conducted at the water storage sites (offline and online ponds) to produce high resolution elevation data, generate pond, and field site DEMs and subsequently extract key elevation metrics/thresholds. Using these DEMs, stage to volume conversions were also possible, to determine the dynamic storage function of these ponds. Flights were performed using a DJI FC350 Inspire 1 drone (4000x3000 res, with a pixel size of 1.56x1.56um), flown at a 100m altitude to generate a ground resolution of 1.61cm/pix, with an overlap of >9 images. Gaining high-resolution surveys for sites was advantageous to determining the storage capacity of structures and the site characteristics in great detail. Flights were not carried out at the Marcombe Lake site as the heavily forested valley would have omitted almost all ground surface from the produced DEM/Orthomosaics. Prior to flights at each site, ground control points (GCPs) were deployed across the site, at varying elevations and distances (for example see Figure 2.13). To ensure distinctiveness from an aerial view, these GCPs were designed as a black 50x50cm square, topped with a white cross (Figure 2.13). These were georeferenced using an OS total station and prism pole from two reference readings on the site. The converted total station data was inputted as markers within SfM software, Agisoft Photoscan (version 1.4.5), within which the aerial images were processed. Sensitivity tests were conducted to find the optimum workflow for data processing, which included reducing marker error to <10cm using camera optimisation tools and removing those markers with high uncertainty.

2.5.3. Manual site surveying for DEM production

To supplement the drone SfM DEMs produced at the offline and online water storage pond sites (presented in chapters 3 and 5), manual NFM pond surveys were also conducted (see Figure 2.13). Whilst the production of SfM drone DEMs provided a number of advantages in terms of scale and high-resolution, the elevation values extracted from ponds under deeper water (notably for >20cm) were found to be unrealistic, based on pond walkovers. This was a particular issue due to deeper pond water during the winter period when drone surveys were conducted to minimise the occurrence of vegetation. The addition of manually surveyed ponds ensured greater pond DEM accuracy.

Figure 2.13. Manual surveying methods, where images show firstly an example of GCP marker at Halsewater used to georeference drone SfM DEMs (a). A total station (b) and prism pole (c-d) were used to gain 200+ topographic points per pond.

These were produced using an OS total station and prism pole to produce angle and distance data, relative to the total station. The prism pole was moved in and around each pond to gain 200+ points per pond to ensure the full shape was characterised and the full topography range was represented. This topographic data was processed using reduction processes in n4ce (v.4.10d), where the inputted angle (horizontal and vertical) and distance data, along with known GPS positions of the total stations and a back reference, was converted to XYZ coordinates. This coordinate data was used to produce individual pond DEMs by creating a triangulated irregular network (TIN), converted to raster format in ArcMap (version 10.6).

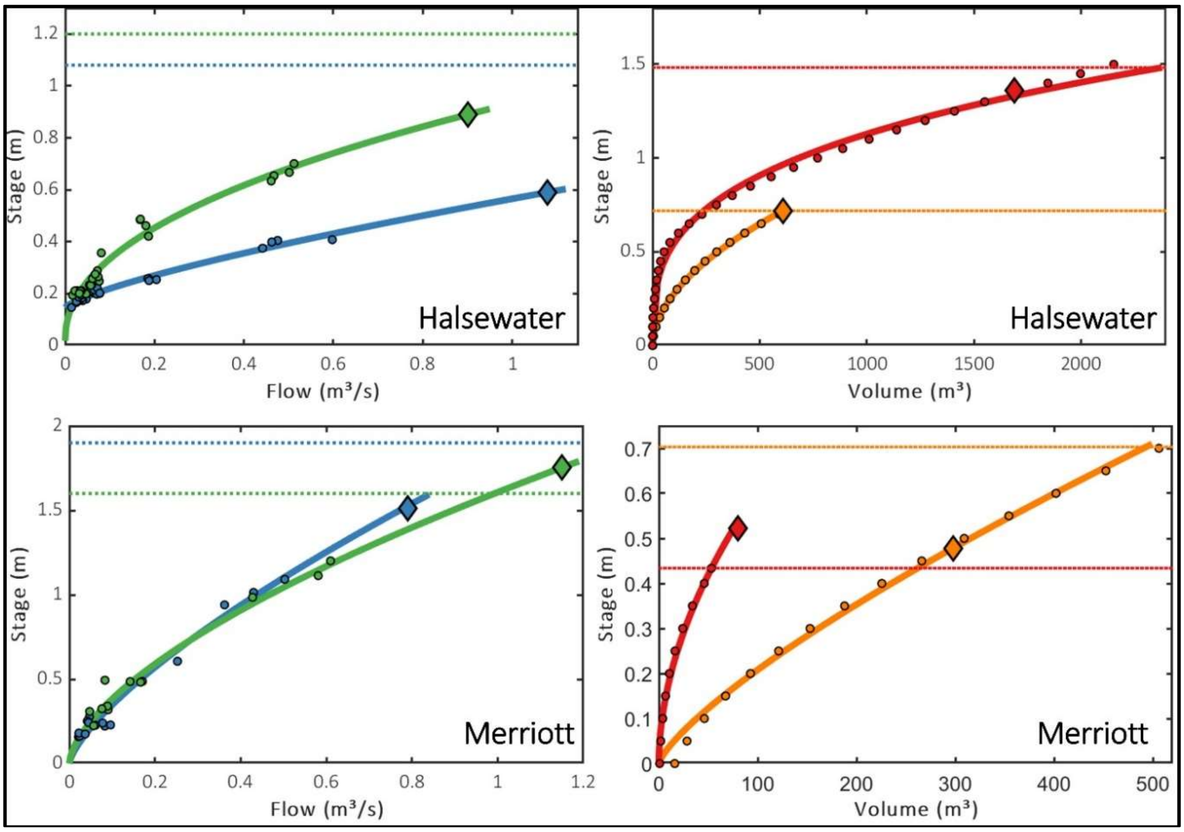
2.5.4. Channel and pond raw level conversions to flow and storage

Channel level data were converted to discharge through the establishment of a rating curve from stage-discharge data collection. Readings were collected by establishing a constant cross section at each in-channel gauge, marked with a stake either side of the river connected with wire. Using velocity-area methods, the stage and corresponding velocity were measured at 10cm intervals across the channel. Velocity was measured using a Model 801 Electromagnetic Open Channel Flow Meter (Valeport), recording a 60 second mean (m/s). Subsequently discharge was calculated by summing each 10cm cell. This process was repeated across the monitoring period, to include low and high flow periods. Lower flow ratings were generally collected in conjunction with regular data downloads, every 2-4 weeks (for example, see Figure 2.14a-b). Gaining the high flow ratings required estimations of when higher channel flow might occur. These estimations were largely based on forecasted storm events (eg. checking rainfall radar maps), whereby data collection would be planned to coincide with the time of rainfall event peaks at each site (for example, see Figure 2.14c-d).

Figure 2.14. Stage-discharge rating data collection during lower flows, at Marcombe Lake (a) and Halsewater (b) in June 2019 and during higher flows at Halsewater, where images show upstream rating (c) and downstream rating (d) in February 2020.

In total 28 discharge measurements (from ratings) were collected for Halsewater for both the upstream and downstream gauge, 14 for Merriott for the upstream and downstream gauge and 14 for Marcombe Lake for gauges 1, 2, 3 and 4. Figure 2.15 presents the rating curves produced for each respective site. Curve extrapolation was required for stages >0.59m for Halsewater's upstream gauge, >0.93m for Halsewater's downstream gauge, >1.05m for Merriott's upstream gauge and >0.98m for Merriott's downstream gauge. In addition, for stages >0.25m, >0.22m, >0.21m and >0.27m for Marcombe Lake's gauge 1, 2, 3 and 4 respectively. Extrapolation was required for the highest discharges due to channel inaccessibility during the very highest flows. These highest peaks occurred very infrequently, often for a very short period of time and often coincidentally throughout the night meaning fieldwork was infeasible.

Pond level data was converted to volume, also through the establishment of a rating curve from the known pond volume per level of water. Pond volume data was generated using ArcMap's volume tool, using the manually surveyed pond DEMs and surveyed logger. The volume of water within each pond for a given water level was determined using a reference plain, set to 5cm water level intervals. This produced a dataset that illustrated at a 5cm interval the corresponding pond volume value for each pond stage value. Using this, a stage-volume rating curve was produced using the stage-volume data for each pond. This was fitted using a power law equation, where individual conversions were produced for each water storage pond (upstream and downstream at Halsewater, Merriott and Wellhams). Figure 2.15 illustrates the stage-volume rating curves for all study sites.



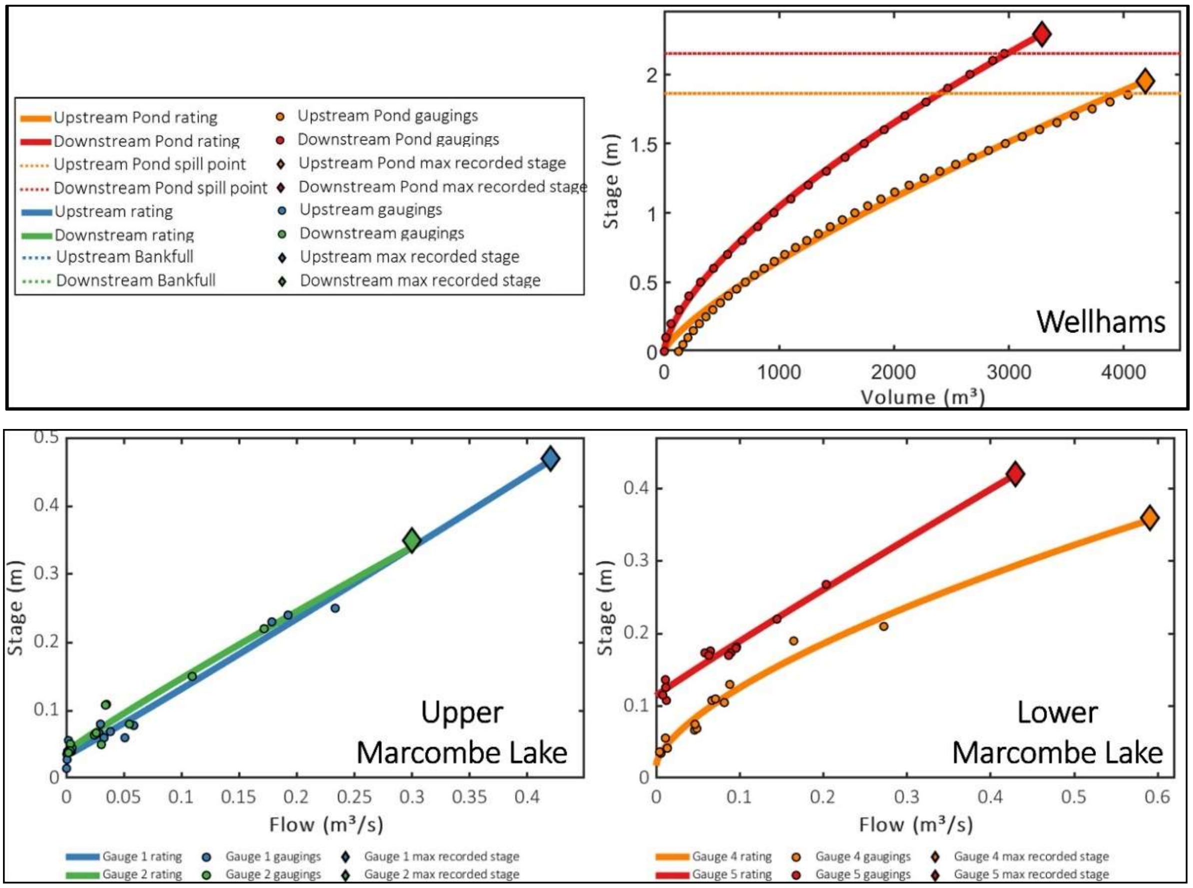
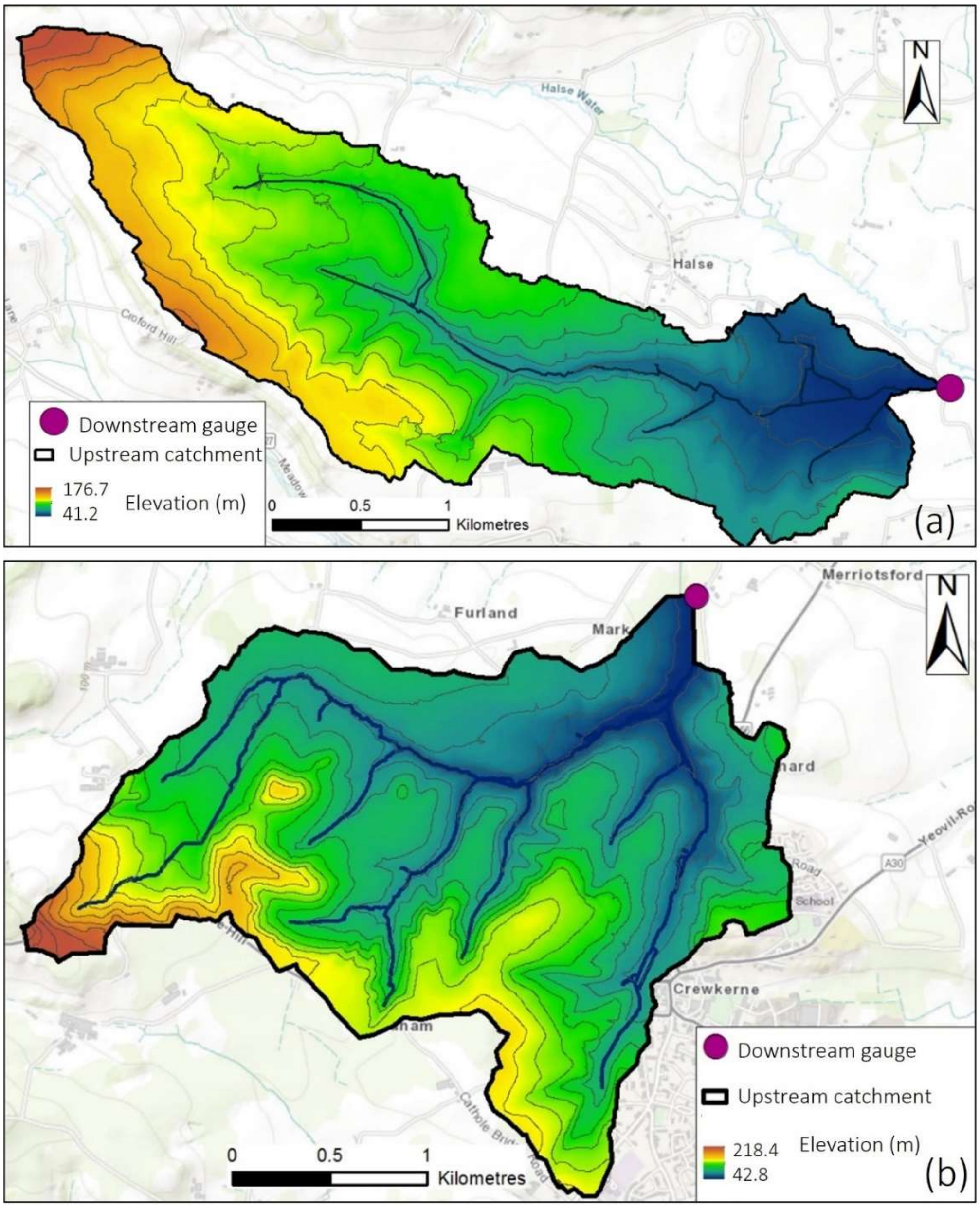


Figure 2.15. Gauge rating curves, converting stage data to flow and volume for respective channel and pond gauges at Halsewater, Merriott, Wellhams and Marcombe Lake. Detailed are maximum stage and pond filling and spilling thresholds, derived from study site DEMs.

2.5.5. Upstream catchment area

The catchment boundaries and upstream catchment area of each deployed channel gauge was calculated using the digital terrain analyses (DTA) for DECIPHeR (Coxon *et al.*, 2019). For the DTA, the following input files were used: 2m LIDAR Composite DTM (EA, 2019), list of gauge location coordinates and a river network file (OS MasterMap Water Network (OS, 2019)). Upstream catchment areas (based on the most downstream deployed gauge at each site) were 6.18km^2 for Halsewater, 6.1km^2 for Merriott, 0.96km^2 for Wellhams, and 1.05km^2 for Marcombe Lake. The calculated upstream boundaries were able to illustrate the upstream topography (Figure 2.16), which correspond with those produced by the EA Catchment Data Explorer.

In addition, these catchment areas were used to illustrate the illustrate landcover, which is important to evaluate additional factors that may influence channel dynamics. The produced land use maps (Figure 2.17) demonstrate that the upstream catchments are dominated by arable and horticulture (Halsewater) or improved grassland (Merriott, Wellhams and Marcombe Lake), with some broadleaved (floodplain) woodland and suburban landcover covering the most headwater locations.



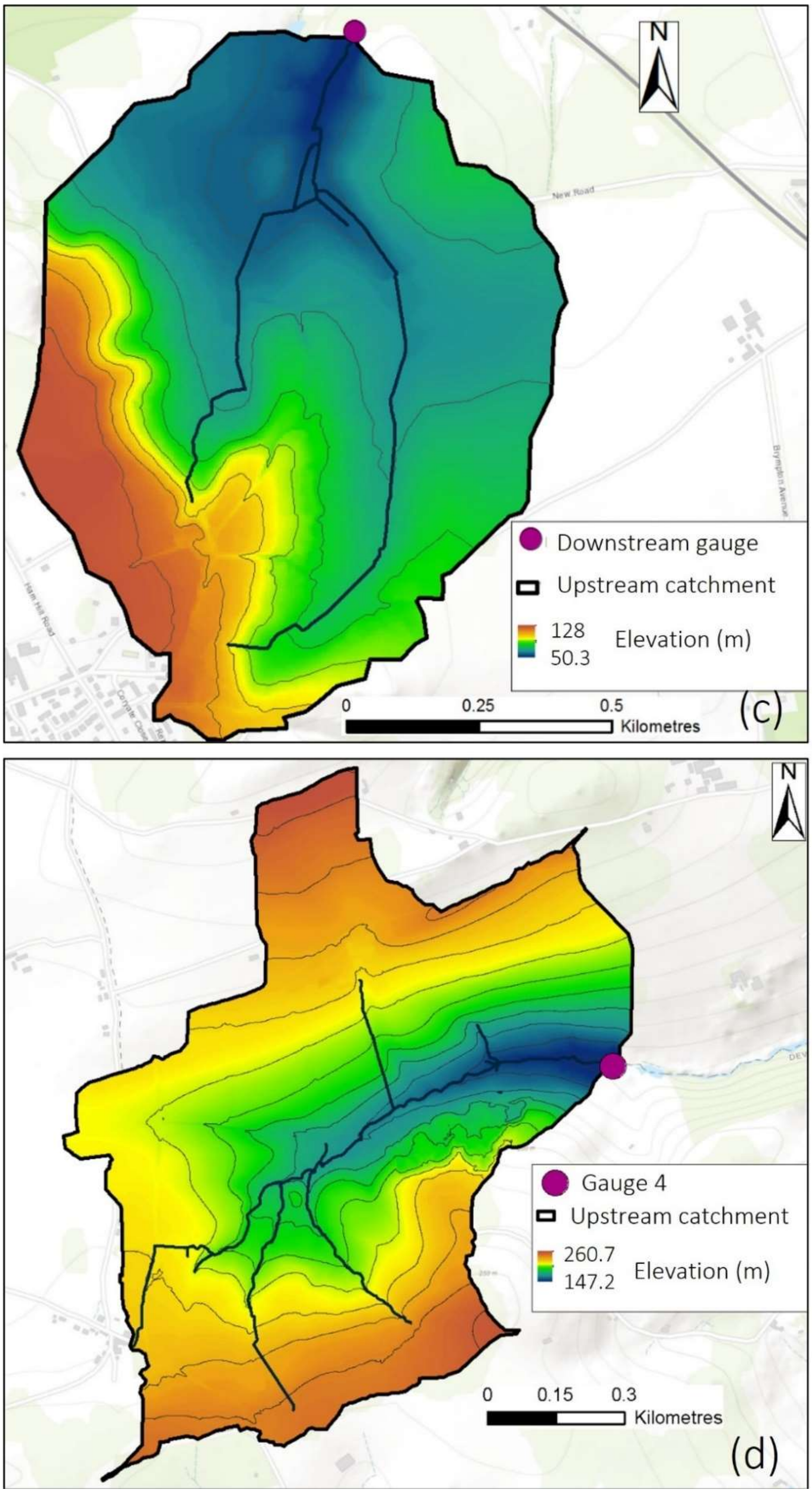


Figure 2.16. Upstream catchment area DEMs (2m resolution) for the river channel field sites: Halsewater (a), Merriott (b), Wellhams (c) and Marcombe Lake (d).

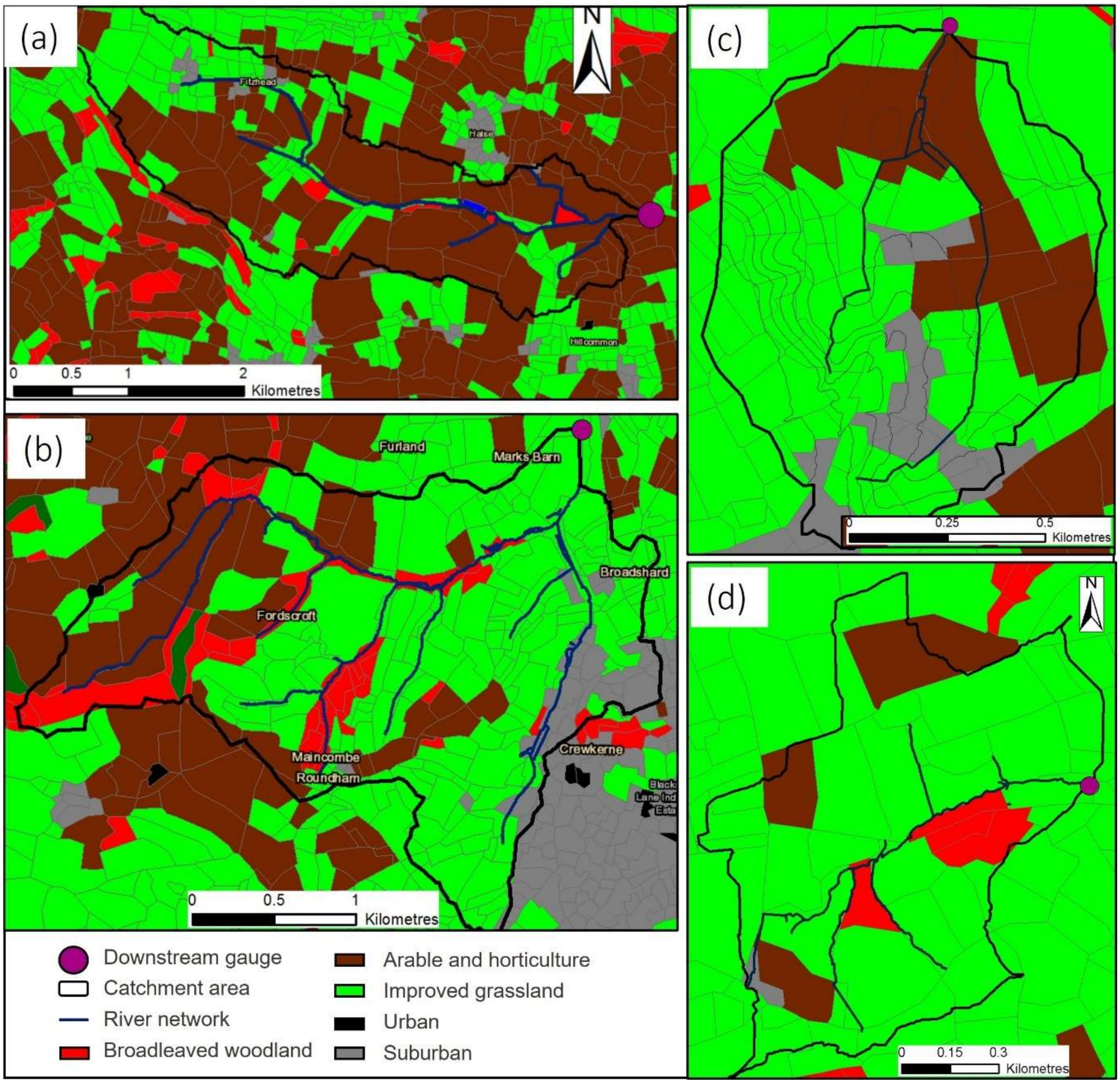


Figure 2.17. Landcover of the upstream catchment area for river channel field sites: Halsewater (a), Merriott (b), Wellhams (c) and Marcombe Lake (d). Accessed from EIDC land cover maps (2019) .

2.5.6. Data pre-processing and rainfall event separation

Site flow and volume data were smoothed using wavelet denoising to reduce noise and ensure distinct hydrograph signals, following sensitivity tests to ensure no hydrograph peaks were lost, lowered, or delayed, but baseflow noise was reduced. Figure 2.18 illustrate an example of this for Halsewater downstream flow. These methods reduced data noise, ensuring only one rise and fall in an event hydrograph (for a single-peak event). As illustrated, the data noise in the raw data produce many very small rises and falls, which were not accounted for in the workflow codes. Using wavelet denoising produces a smoothed dataset, whilst ensuring peak heights are not significantly altered.

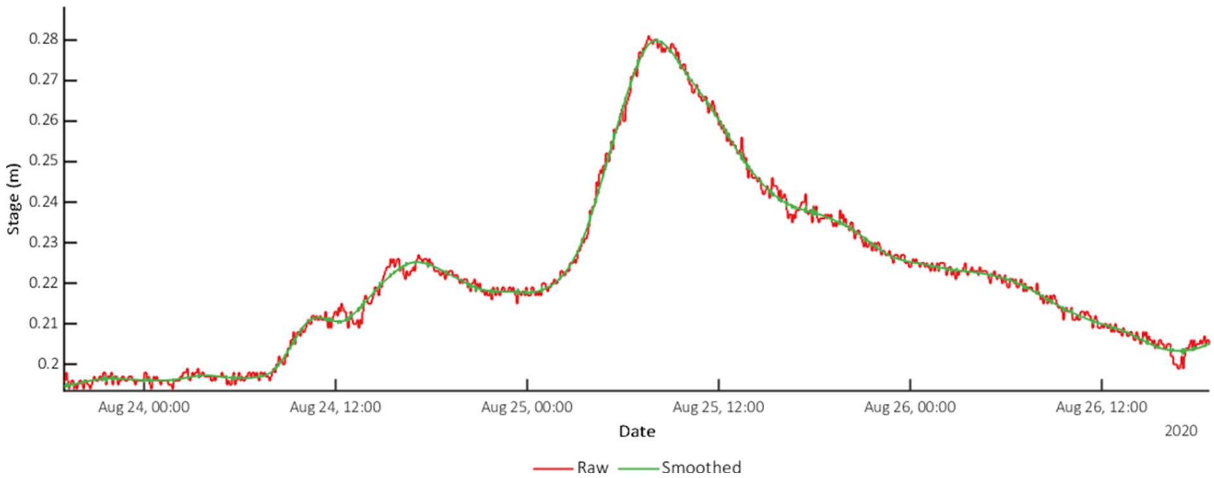


Figure 2.18. Example of data smoothing for Halsewater downstream flow. Illustrated is raw data (pre-smoothing) and smoothed data.

To systematically sort and separate the collected rainfall, flow, and volume data at the four river channel sites into distinct events, a rules-based event definition workflow was developed in MATLAB (2019b). This was important to ensure that consistent rules were taken for all events to gain a consistent and realistic set of metrics. The following workflow was utilised by chapters 3-5 to separate data at Halsewater and Merriott (chapter 3), Marcombe Lake (chapter 4) and Wellhams (chapter 5). These key workflow methods that follow are also conceptualised by Figure 3.3 (see chapter 3).

Rainfall event separation

Using the rainfall dataset (0.2mm, 1min resolution), rainfall data was combined into separate events based on a minimum inter-event (MIT) of 3 hours. (Deasy *et al.*, 2014). This MIT was determined from visual examination to ensure that separate events were kept distinct, whilst acknowledging that consecutive bursts of rainfall within a small-time frame constitute a multi-peak event, for example, where flows remain high, with no return to baseflow. As the first stage of event separation, this separates all possible rainfall events, with no minimum event length or volume at this stage. Then, using these grouped rainfall periods, the event start is defined as the first timestep of continuous rainfall, where there is >0.6mm over a 15-minute period. This threshold for continuous rainfall was selected to ensure that the event start constituted the first part of continuous rainfall. For example, without employing such a threshold, the event start may have occurred from a single rainfall tip monitoring up to 3 hours (MIT period) prior to the remainder of the event rainfall.

Subsequently, further key metrics were extracted from these grouped rainfall periods. These were the total event rainfall depth (mm), API value and rainfall duration. At this stage, as all possible rainfall occurrences are included, a minimum event rainfall depth (3mm) and event duration (30mins) is applied to ensure all event analysis concerns plausible rainfall periods. Whilst this doesn't introduce any great bias in regard to what constitutes a rainfall event, it does remove anything that in reality is just a few tips of the tipping bucket rain gauge.

Flow event separation

These rainfall events were then matched with the relevant flow and volume data for each site, using the same datetime periods. Further key metrics are extracted for the relevant event start flow and volume values, based on the rainfall event start time previously defined. Additionally, the event peak is defined as the highest rainfall data value between the start of the current rainfall event and the start of the next rainfall event. This value is extracted for all gauges at both sites.

Event end is extracted as the time point when flow return to the pre-event baseflow, within a 10% threshold. This was selected to achieve near-baseflow conditions, whilst acknowledging that depending on catchment conditions, flow rates are unlikely to quickly decline to exactly pre-event values, particularly in large events. If this does not occur (no value within 10% of pre-event flow) before the next separated rainfall event, then the event was omitted from analysis for Halsewater, Merriott and Marcombe where complete hydrographs are needed for analysis. For Wellhams, the event end is simply defined as 2 hours before the following event if there is no value within 10% of pre-event flow as the effects of in-channel pond storage, mean that a return to pre-event volumes is unlikely (see chapter 6 for further details).

In addition, it is important to note that these events (where flow does not return to baseflow (within 10%) before the next event, are different to multi-peak events. Multi-peak events are defined in the workflow as events with multiple peaks, which match with a corresponding number of rainfall bursts (with no rainfall breaks >3 hours, as per the defined MIT. Single-peak events present just 1 distinct burst of rainfall within the MIT of 3 hours. Importantly, in between the peaks, flow decreases below 75% of the flow peak value. As an example, for a 2 peak multi-peak event, this will show 2 occurrences of flow rising and falling below the 75th percentile.

Larger events are of most interest for these studies because the impacts of NFM for flow attenuation and floods are the focus in this thesis. Indeed, small events are largely expected to produce negligible responses as a result of NFM impacts. Therefore, the top 30% events were further separated according to the downstream rise amount (5th-95th percentiles). Using these events, the impacts of NFM structures for a range of hydrological metrics were analysed. These metrics and their rationale for study at each site are detailed in chapters 3-5.

Finally, there are data gaps periods for certain sites (for example, due to site access restrictions seasonally at Halsewater, one occurrence of human error at Merriott and site inaccessibility at Merriott). To ensure complete flow and volume datasets for all events, any event with missing data is omitted.

Hydrograph percentile separation

To analyse the impact of the monitored NFM features, further separating all event hydrographs according to percentile values was of particular importance. This was utilised for event flow data at Halsewater and Merriott (chapter 3) and at Marcombe Lake (chapter 4). Using the downstream flow data, the 0th, 5th, 25th, 75th and 95th percentile values were extracted, which represented the percentage of flow values between the event start (0^{th}) and event peak (100^{th}). This is applied to the rising limb (event start to event peak) and falling limb (event peak to event end) of each separated event. The downstream flow values and associated timestamps were extracted for each event. Then using these timestamps, the associated values for all other gauges at each site were extracted.

For flow volume analysis, these extracted percentiles are used to group the separated events into parts of the rising and recession limb, for the 5^{th}-25^{th}, 25^{th} – 75^{th} and 75^{th}-95^{th} percentiles. The 95^{th} rising limb to 9^{th} recession limb is used to extract the event peak values, to gain a more representative and average value (than selecting a singular highest flow value as the peak). Site-specific event metrics that were used to examine the impact of the NFM features are detailed within their respective chapter.

2.6. Hillslope NFM study sites

In this section, the five hillslope NFM sites will be introduced, where sampling and testing occurred in the Tone and Parrett catchments. There are marked variety of NFM measures that aim to increase soil storage capacity, by primarily targeting the hillslope. Machinery-based soil management methods are a key example of measures aiming to improve soil structure, increase infiltration and expecting to improve crop yields. These have been conducted through the Hills to Levels project as a result of extensive farm visits and soil husbandry advice. Through these works, soil management trials have been conducted across the Tone and Parrett catchments in recent years, with some carried out as part of countryside stewardship grants.

Five soil-management field sites across the Tone and Parrett catchments were selected opportunistically for soil testing and sampling. Corresponding subsoiling methods were assured between all sites, for example where subsoiling was conducted to the same depth and across a sufficient spatial area for sampling with a control section. Figure 2.19 illustrates the locations of these sites in regard to national surface soil silt sand and clay percentages (LandIS National Soil Map of England and Wales (NATMAP). The five study sites tested are firstly summarised by Table 2.3 and are then introduced, although the majority of detail, including soil compositions are provided in chapter 6.

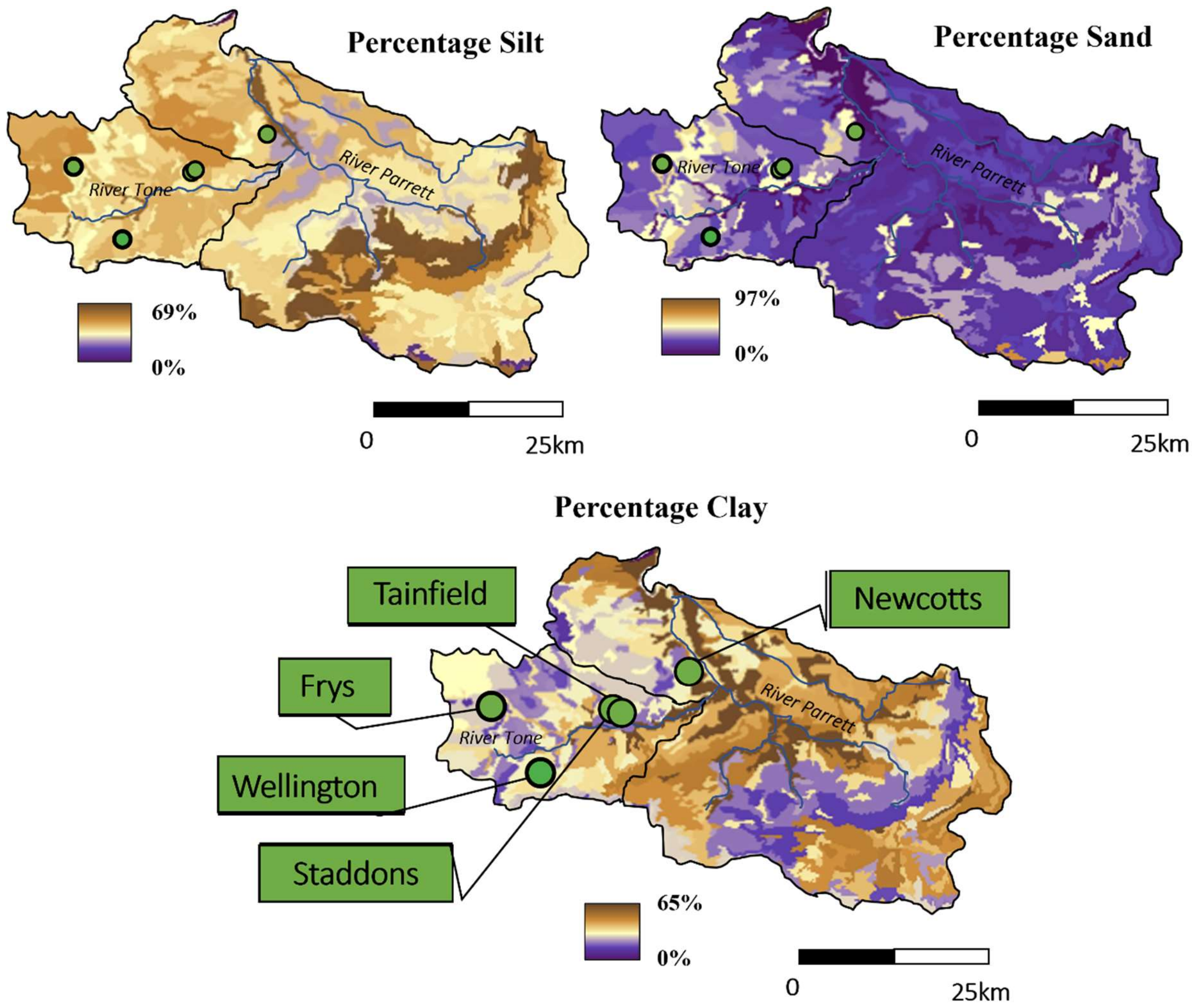


Figure 2.19. Locations of hillslope NFM study sites in the Tone and Parrett catchments according to surface soil percentage silt sand and clay for the Tone and Parrett catchments (adapted from Figure 2.3). Study site names are labelled for the clay percentage map. Raw vector datasets accessed from LandIS National Soil Map of England and Wales (NATMAP). Raw datasets were processed and converted to a 50m raster for Great Britain by Lane (2020). Parrett catchment area was clipped as the area of interest in this thesis.

Site	River/Catchment	Subsoiling trial	Land use
Newcotts	North Moor Main Drain, Parrett	17,000m^2 subsoiled 17,0000m^2 control	Grassland
Frys	Hillfarrance BK, Tone	130,000m^2 subsoiled 10,000m^2 control	Winter wheat
Wellington	Westford Stream, Tone	19,000m^2 subsoiled 35,000m^2 control	Miscanthus
Tainfield	Tone	12,000m^2 subsoiled 36,000m^2 control	Miscanthus
Staddons	Tone	19,000m^2 subsoiled 20,000m^2 control	Miscanthus

Table 2.3. Key details of five soil management study sites. River/catchment information derived from EA Catchment Data Explorer. Trials were conducted by farmers/landowners, who shared key details for these studies, including area of subsoiling trial and specific locations of control and subsoiled field sections.

2.6.1. Newcotts

Newcotts is an arable grassland farm (Figure 2.20), located on average at 10m above sea level. Until relatively recently (before 2018), the field had been used for growing miscanthus crop. At the time of testing the grass had been recently harvested for silage. The underlying bedrock is mudstone and Halite stone, and local soils are dominated by a silt-clay soil texture (see Figure 2.19).

Figure 2.20. Grassland site (recently cut crop at the time of sampling).

2.6.2. Frys

Frys is an arable field (Figure 2.21), where winter wheat is grown, harvested in early autumn. At this site, a 15m strip was used as the control, where the remainder of the field was subsoiled. The underlying bedrock is mudstone/sandstone and local soils are dominated by a loam texture (see Figure 2.19).

Figure 2.21. Images showing winter wheat study site. At the time of fieldwork, crops were well grown and dense, where testing and sampling occurred in between the wheat stems.

2.6.3. Wellington

Wellington is a miscanthus field site (Figure 2.22), where at the time of sampling, crops were dense. Subsoiling was conducted over half of the field and an additional headland. The underlying bedrock is mudstone and local soils are dominated by a loam texture (see Figure 2.19).

Figure 2.22. Images showing miscanthus study site. The density and height of the crops meant that infiltration and soil samples were guaranteed within the sample transect grid.

2.6.4. Tainfield

Tainfield is a miscanthus field site, where two headlands were subsoiled, with the remainder used as a control. The crop was notably sparse at this site. The underlying bedrock is slate and local soils are dominated by a loam texture (see Figure 2.19).

Figure 2.23. Images showing miscanthus study site. A split between the control and subsoiled areas of the field was visible by a divide in vegetation (a), with large areas of sparse crop (b).

2.6.5. Staddons

Staddons is a miscanthus field site, where the four edges of the field were subsoiled, with the centre used a control (see Figure 2.24). The crops were markedly denser at this site, relative to Tainfield (both sites were located within the same farm). The underlying bedrock is slate and local soils are dominated by a loam texture (see Figure 2.19).

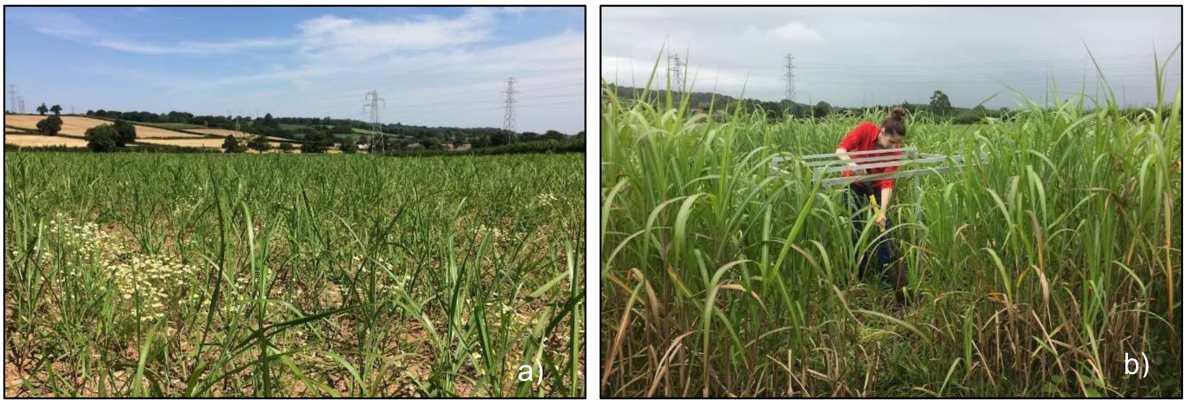


Figure 2.24. Images showing Staddons miscanthus study site (a), with a higher crop density and height, particular at the field headlands (b)

2.7. Hillslope-based NFM study site methods

The following section will detail the key methods conducted at the hillslope NFM study sites in this thesis, from testing through to analysis. It is important to note that the details provided here are to provide an introduction and background to the methodologies carried out in chapter 6, where the majority of detail is presented in that chapter under section 6.3 (data and methods).

Firstly, the soil physical and hydraulic property testing methods are introduced, to include measurements for bulk density, laser diffraction and loss on ignition for compaction, particle size and soil organic carbon respectively. Secondly, the use of a rainfall simulator to conduct plot-scale runoff experiments is outlined.

2.7.1. Soil physical and hydraulic property testing

Physical soil properties were tested for bulk density and soil organic carbon. These properties were chosen based on their wide use to characterise soil structure, health, and compaction, which are inherently linked to the water holding capacity of soil (Da Silva *et al.*, 1997). In addition, rainfall simulations were conducted to quantify the impact of subsoiling infiltration, overland flow, and sediment yield at the plot scale. These methods are briefly summarised by Figure 2.25 and are detailed in chapter 6.3.

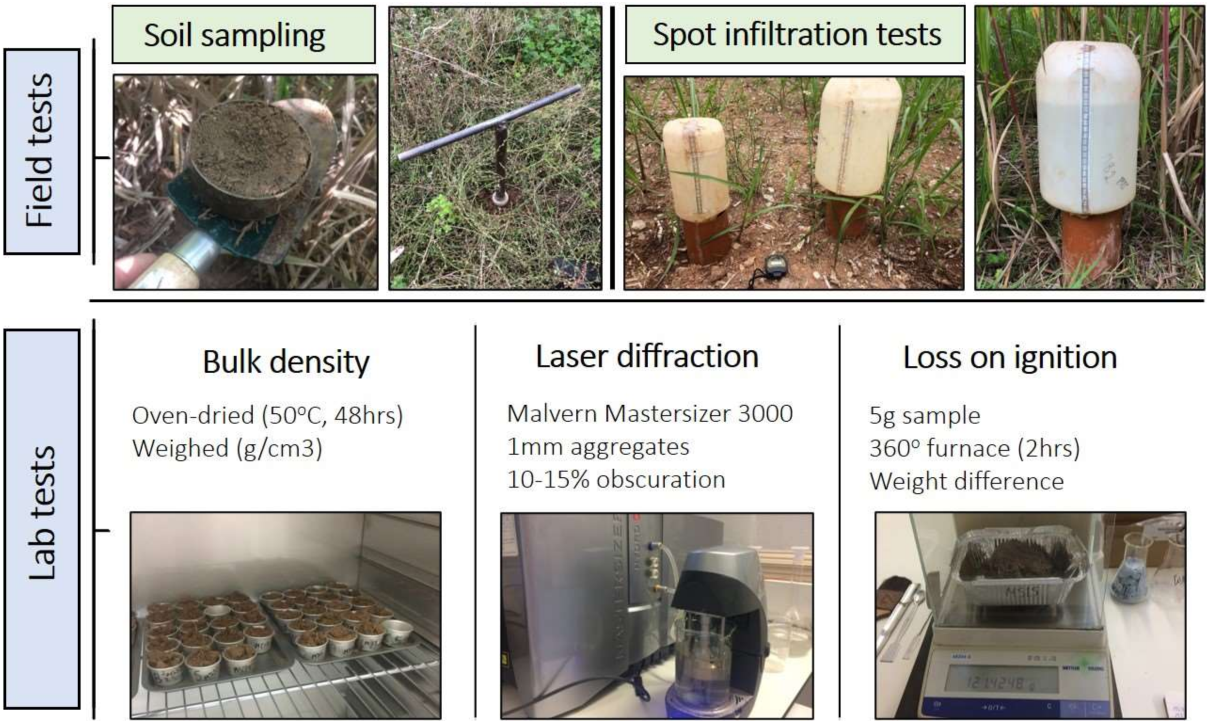


Figure 2.25. Soil sampling using hand-held soil augers (20cm depth) and bulk density rings were conducted in the field. In the lab, soil samples were tested for particle size distribution (laser diffraction), soil organic matter (loss on ignition) and compaction (bulk density).

2.7.2. Rainfall simulations

Rainfall simulations were conducted to gain infiltration, runoff, and erosion values. All rainfall simulations could not be conducted on the same day due to time constraints and so were carried out over a month, spreading out site and plot types. Figure 2.26 illustrates examples of simulation setup, including building of the simulator frame (Figure 2.26b) and digging in plot sides (Figure 2.26d). There is sparse crop and weed vegetation cover at Tainfield plots, compared with the medium crop density at Staddons (Figure 2.27). The methods used, including full details on the rainfall simulator setup and subsequent analysis are presented in chapter 5.

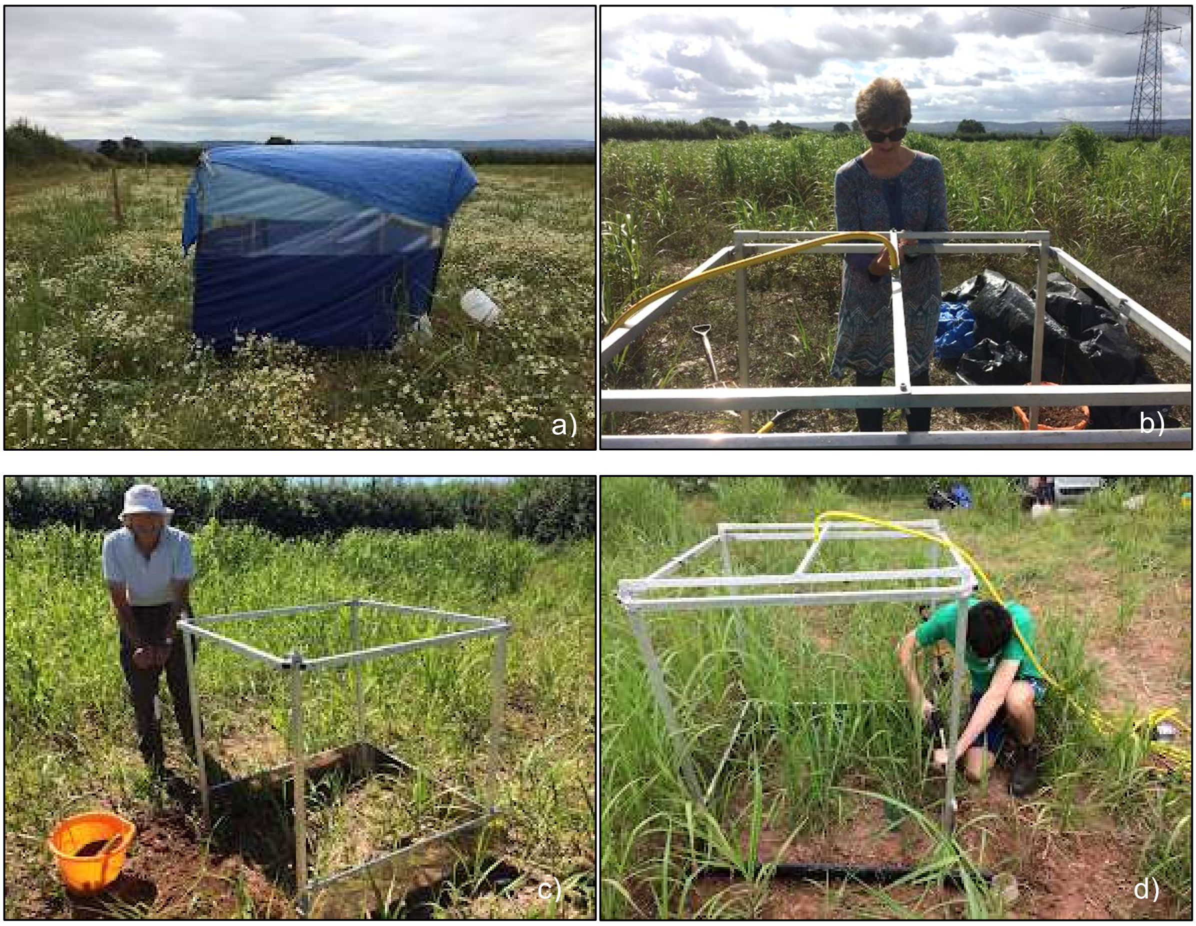


Figure 2.26. Initial site walkovers and pilot rainfall simulations in the field (a) and subsequent simulations at Staddons (b) and Tainfield (c-d).

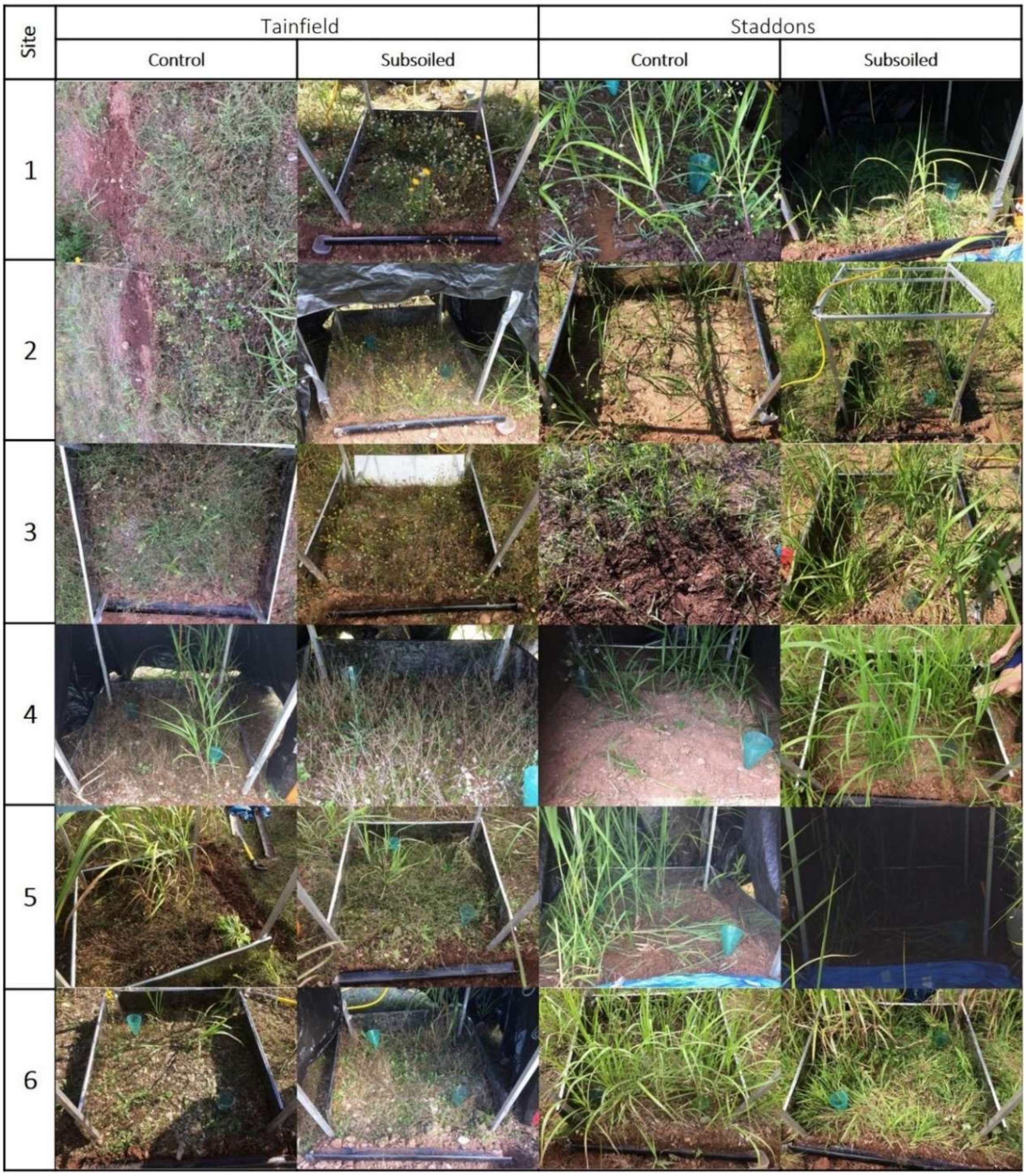


Figure 2.27. Rainfall simulation plots and setups. Tainfield plots are dominated by weeds and sparse crop growth, whilst Staddons plots had a denser coverage of miscanthus.

2.8. Field research timeline

To generate the empirical datasets required (eg. to capture a range of rainfall events), in-situ monitoring equipment had to be installed within the first period of this research project. As data collection for chapter 6 relied on the occurrence of subsoiling trials, this fieldwork extended across the course of the PhD, in response to field site availability. Figures 2.28 and 2.29 illustrate timelines for installations, monitoring and testing for channel and hillslope-based features respectively.

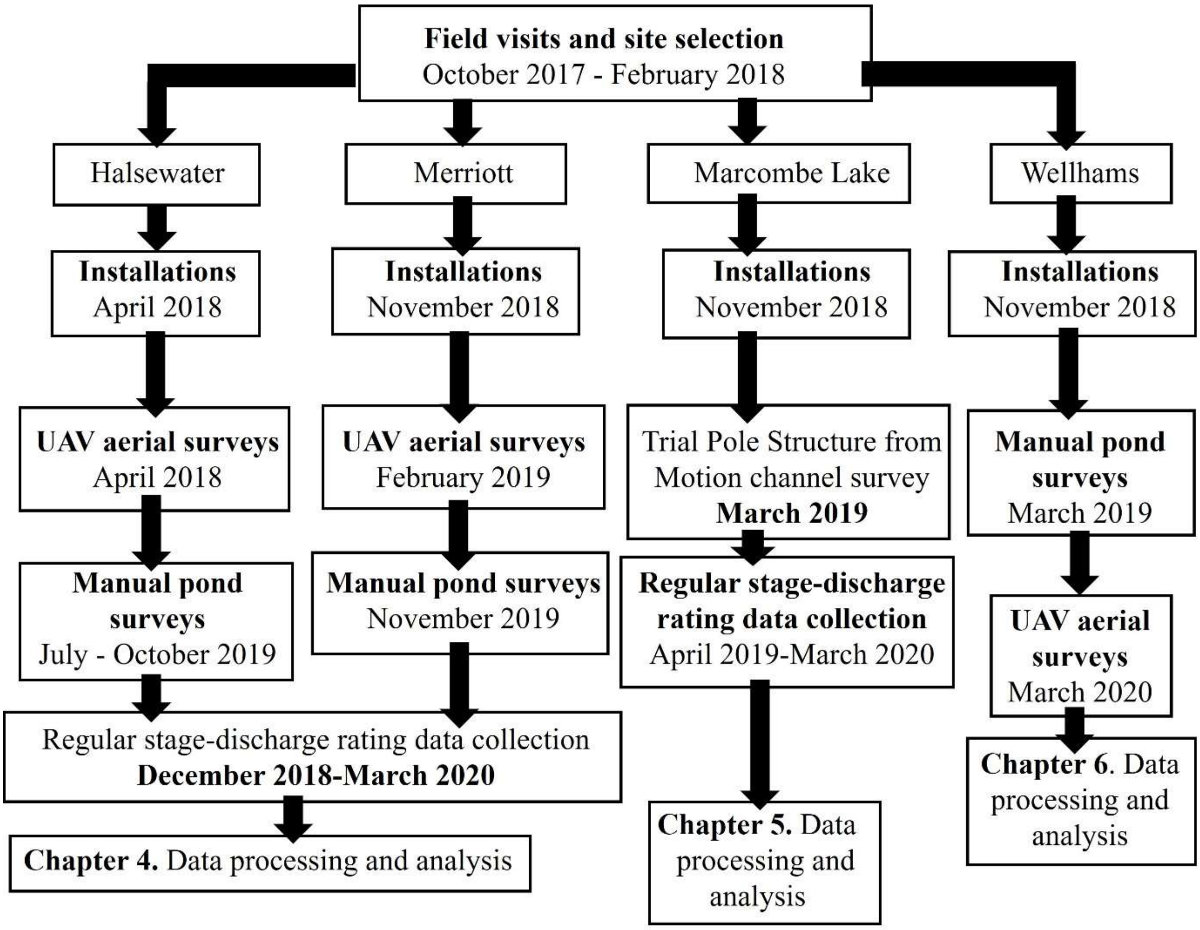


Figure 2.28. Fieldwork timeline, illustrating key methods for data collection for the production of channel based NFM datasets, for insertion within chapters 3, 4, and 5.

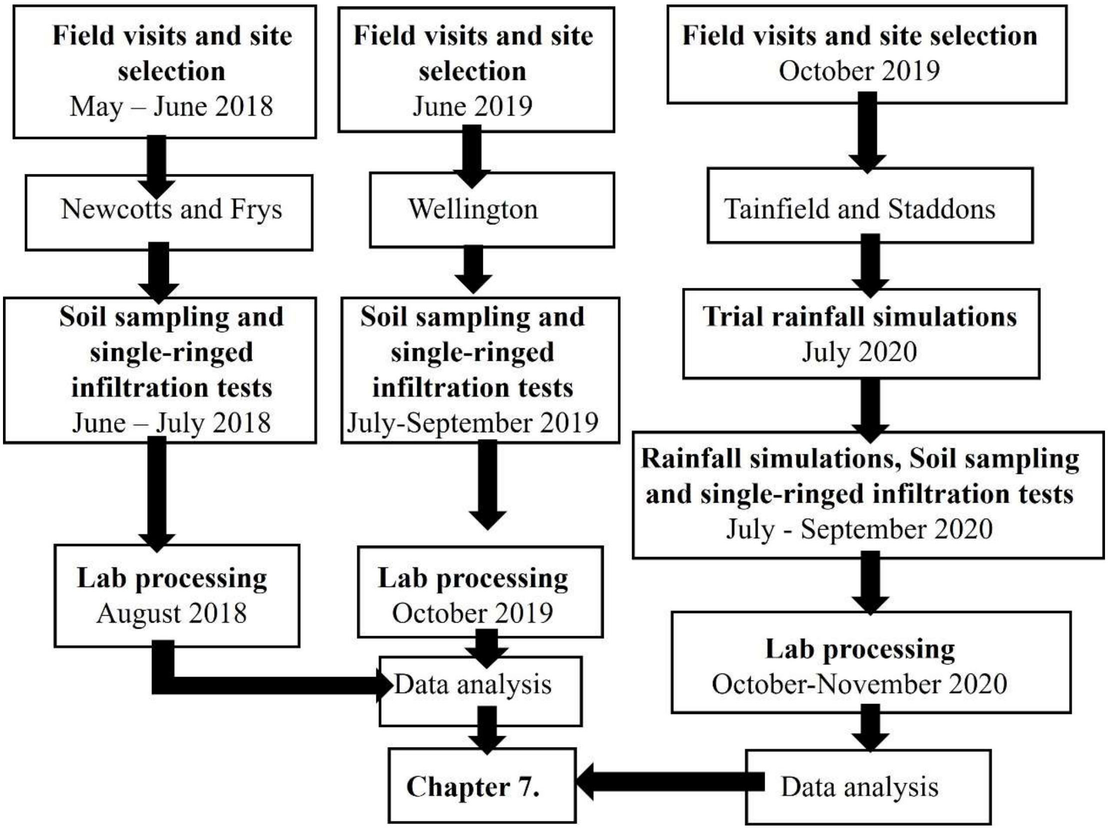


Figure 2.29. Fieldwork timeline, illustrating key methods for data collection for the production of hillslope based NFM datasets, for insertion within chapter 6.

3. Assessing the efficacy of offline water storage ponds for Natural Flood Management

This chapter has been published as a paper by Hydrological Processes. It has been adjusted for inclusion here to fit with the content of the other chapters. Data collection, analysis and Figures were produced by Tamsin Lockwood, with guidance from Jim Freer, Gemma Coxon and Katerina Michaelides and Richard Brazier. The manuscript was written by Tamsin Lockwood, with comments from all co-authors.

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3.1. Context

Research question 1: What is the efficacy of offline water storage ponds for Natural Flood Management?

The potential for NFM storage structures to attenuate flow is gaining increasing interest in the UK and globally. However, current evidence for their function and impact in the landscape is based on a limited number of empirical datasets. Further analyses and field data is required that evaluate the impact of storage structures across rainfall events, to consider their impact on downstream flows. This research chapter includes the development of an event separation methodology to define individual rainfall events and the corresponding flow and storage pond behaviour to analyse their function and impact on downstream flows. This enables a comparison of the impacts of two contrasting offline water storage pond designs in the Tone catchment, Somerset, including recommendations for future design. This chapter aims to assess the impact of design, management, and hydrological inputs of offline water storage pond function. In addition, to evaluate the dynamic hydrological response of offline water storage ponds to rainfall events, based on their ability to fill, store, and spill stormwater.

3.2. Introduction

Natural Flood Management (NFM) encompasses mitigation strategies that aim to restore hydrological and morphological catchment features, to enhance downstream flood resilience (Dadson et al. 2017; Lane 2017). Historically, modern society has relied upon technical and engineered flood management to mitigate flood risk. However, hard engineered structures have negative ecological impacts and limited consideration of wider catchment processes, often focussing on simply diverting floodwater further and faster downstream (Ellis *et al.*, 2021). In recent years, there has been a growing effort to enhance flood risk legislation, in recognition of the multiple co-benefits associated with NFM, and to address mitigation measures across the catchment (Iacob *et al.*, 2014; Bracken *et al.*, 2016; Williams *et al.*, 2020). Numerous interventions, including river and floodplain restoration, woodland management and runoff control, have been piloted across UK (Environment Agency 2017; Scottish Environment Protection Agency 2015) and European catchments (Meyer *et al.*, 2012; Van Wesenbeeck *et al.*, 2014; Hartmann *et al.*, 2019; Santoro *et al.*, 2019). Designed to attenuate floodwater peaks and slow catchment flows, NFM has been defined as a key future solution for flood risk reduction, to complement engineered methods and build resilience under changing climates (Environment, 2019; HM Government, 2019; Ellis *et al.*, 2021).

NFM encompasses a range of flood management structures and schemes. These include leaky woody dams (Thomas and Nisbet, 2012; Dixon *et al.*, 2016; Deane *et al.*, 2021), floodplain afforestation (Birkinshaw, Bathurst, and Robinson 2014; Marshall et al. 2014; McIntyre and Marshall 2010; Thomas and Nisbet 2007), land and soil improvements (McIntyre and Marshall, 2010) and beaver dams (Puttock *et al.*, 2017, 2021). One further, widely applied strategy are water storage ponds, designed to increase floodplain surface water storage over a smaller area than alternative NFM storage potentials such as floodplain reflooding or restoration, for instance as a result of flood embankment removal (SEPA, 2015). Water storage ponds are designed to emulate naturally occurring ponds or farm ponds, which since the agricultural revolution have dramatically reduced in numbers in the UK and globally, as a result of agricultural intensification (Davidson, 2014). Through NFM, water storage ponds may reinstate the large amounts of surface water storage that have been lost. Ponds may be constructed ‘online’, where storage is developed in-channel, and flow is typically held by an outlet structure (De Martino *et al.*, 2012). Alternatively, ‘offline’ ponds direct flow onto the floodplain via an inlet, where it accumulates, usually behind a retaining bund, before being released at a slower rate back into the channel. Dynamically, these interventions should maximise flow attenuation during high flow events, reducing storm outflow and lowering hydrograph peaks (Quinn *et al.*, 2013). Wider benefits have also been reported, for example through pollutant retention due to sediment accumulation and habitat creation (Verstraeten and Poesen, 1999; Morris *et al.*, 2003; Barber and Quinn, 2012; Janes *et al.*, 2017).

Despite growing evidence that ponds can be effective for reducing flow peaks at the local scale (Quinn *et al.*, 2013; Nicholson *et al.*, 2019), there is a lack of scientific evidence underpinning pond functioning and a robust assessment of their efficacy for different flows (Environment Agency, 2017). This is a key hindrance to stakeholder and landowner engagement (Wells *et al.*, 2020; Garvey and Paavola, 2021), where cooperation is vital for NFM uptake (Howgate and Kenyon, 2008). Pond efficacy, whereby structures sufficiently fill, store and spill water at appropriate times to slow and lower storm water peaks, is dependent on numerous factors. These include catchment-scale, location, antecedent conditions, management, and maintenance, along with total storage capacity, meaning their exact function for a given storm magnitude is complex. Assessments of NFM ponds in the literature extract key hydrological characteristics of recorded events, such as peak flow, lag times and flow duration, typically comparing gauges upstream and downstream of interventions, along with individual pond volume change (eg. Wilkinson *et al.*, 2010; Metcalfe *et al.*, 2017; Nicholson *et al.*, 2019). Generally, there is a focus on extracting a few, chosen storms for analysis, considering the largest events, based on rainfall or antecedent conditions (eg. Wilkinson *et al.*, 2010; Metcalfe *et al.*, 2017; Nicholson *et al.*, 2019) or by selecting contrasting events, for example, summer/winter or larger/smaller (eg. Nicholson et al. 2019; Quinn et al. 2013). Elsewhere, a rules-based approach to rainfall event and flow response extraction has been employed (eg. Deasy *et al.*, 2009; Luscombe, 2014; Puttock *et al.*, 2017; 2021), enabling analysis of the full range of captured events and NFM response to understand the lower and upper limits of water storage and flow attenuation.

NFM ponds have also been conceptualised in hydrological models to develop our understanding of their impact on storm runoff (see De Martino et al. 2012; Metcalfe et al. 2017), enabling scenario analysis of different pond combinations across catchment scales. In Nicholson et al. (2019) a network pond model was built on the 2007-12 monitoring campaign (Wilkinson *et al.*, (2010) and Quinn *et al.*, (2013)) in the Belford Burn catchment, Northumberland (UK). This showed ponds to have a greater impact on a hydrograph rising limb, rather than on peak flow, although storage was shown to reach capacity by the peak, reducing flood attenuation potential. Indeed, Belford ponds only demonstrated effectiveness during smaller, flashy events. This was attributed to the design of the structure, where during larger recorded events, pond filling commenced approximately 10 hours before the peak.

To expand on emerging modelling methodologies that assess the impact of NFM structures (eg. Quinn *et al.*, 2013; Metcalfe *et al.*, 2017, 2018; Nicholson *et al.*, 2019; Ferguson and Fenner, 2020; Follett *et al.*, 2020; Goudarzi *et al.*, 2021) and additionally to aid opportunity mapping (Hankin *et al.*, 2017; Lavers and Charlesworth, 2018; Barnsley *et al.*, 2021) the collection of high-resolution empirical data for in-depth event analysis of NFM structures is urgently needed (Black *et al.*, 2021). This will ensure uncertainty and scenario analysis of NFM designs across landscapes are able to quantify their efficacy for flood risk reduction (O'Connell *et al.*, 2004; Thomas and Nisbet, 2007; Dixon *et al.*, 2016). In addition, analysis over a full range of events will highlight key points that should be considered in future offline pond design, in order to optimise pond efficacy for flow attenuation.

This study explores the function and efficacy of ponds to attenuate flow for flood risk reduction. From a pool of NFM sites across Somerset, two offline water storage sites of contrasting designs were monitored, for comparison of two key designs deployed in NFM nationally (see case studies of similar storage designs reported in Burgess-Gamble et al., (2018) and SEPA, (2015)). Both offline pond sites were constructed within 5km upstream of areas of historic flooding (see EA, 2022 for map of historic flood extents), where the offline pond design aimed to temporarily store stormwater during high flow winter events. These structures were implemented through the Hills to Levels project: a mitigation response to the 2013/14 floods, as part of Somerset's 20-year Flood Action Plan. This uses a catchment-based approach, whilst providing environmental benefits including local erosion control, nutrient trapping, and habitat improvement. Offline storage ponds have been designed as part of Hills to Levels to improve floodplain to channel connectivity, whilst temporarily holding back water on the floodplain, enabling the slow drainage of flow. These floodplain sites were selected opportunistically, based on their adjacency to a channel with a constant baseflow and on areas of land with minimal productivity (FWAG-SW, 2018). Further details of NFM strategies deployed, including past and current advice and grants for soil improvements, attenuation and storage of runoff and flow can be found in FWAG-SW (2018). Despite widespread uptake across the Tone and Parrett catchments, from an opportunistic NFM implementation plan for local flooding issues, there is little scientific evidence to detail their hydrological function or efficacy for attenuation. This is required to ensure a legacy of this widespread NFM coverage and future scheme optimisation, locally and nationally.

In this paper, we firstly analyse the lower and upper limits at which two contrasting offline pond sites function, based on their hydrological characteristics and structural design. Secondly, we evaluate the efficacy of offline ponds to attenuate storm flow across multi-peak events within a historical context. Finally, we analyse the dynamic hydrological responses of offline ponds to flow events, based on their ability to fill, store, and spill storm water.

3.3. Data and methods

The methodological approach taken in this study involved field-based monitoring of flow, pond volume and rainfall over a 32-month period, at two contrasting offline storage pond sites. Event separation was carried out using a rules-based methodology, where the conditions required for ponds to function and their impact for downstream flow were examined.

3.3.1. Study area

Monitoring sites were established in the Tone and Parrett headwaters, Somerset (SW-England). The River Tone (414km^2) drains the Exmoor, Brendon, Quantock and Blackdown hills, joining the River Parrett (1700km^2) at Burrowbridge and is tidal for up to 30km from the Bristol Channel (Environment Agency, 2009). Study sites comprised of two alternative designs of offline pond sites: 1) two offline ponds (Halsewater, Figure 3.1a), designed to fill connected storage between floodplain bunds, from an inlet, before spilling back into the channel; and 2) two independent, offline ponds (Merriott, Figure 3.1b), with separate inlet and outflows, connecting the river. The two sites differ in terms of their catchment, structural inlet and outlet heights, overall storage capacity, baseflow relative to storm peaks and floodplain connectivity (Halsewater are connected, whilst Merriott are not). See Table 3.1 for further key site details. Based on the EA Historic Flood Map (see EA, 2022), neither sites (or upstream areas) were located where the floodplain was recorded to have flooded historically. Historic surface water flooding was reported within 5km downstream of both sites.

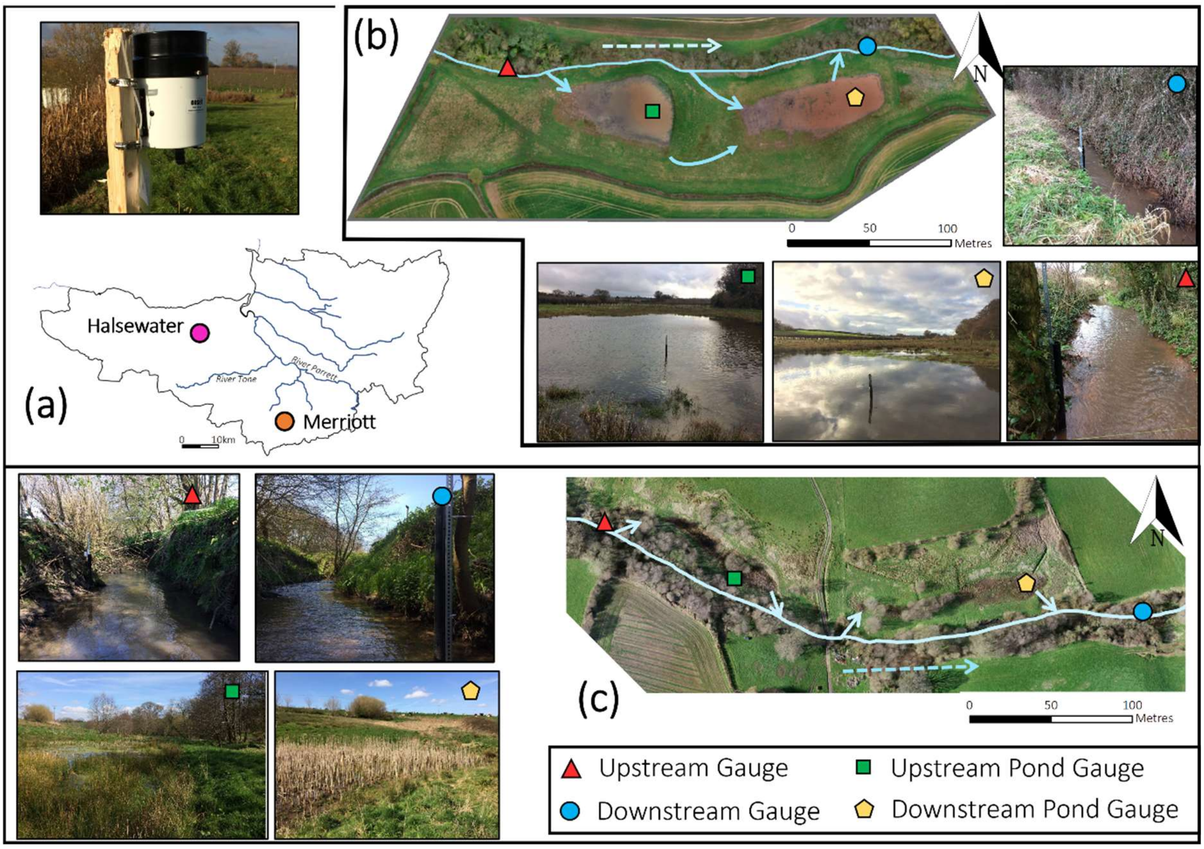

Figure 3.1. Study site locations, situated in the Tone and Parrett catchments, Somerset (a) SW-England. Gauge installations are detailed for (b) Halsewater offline storage and (c) Merriott offline storage, including upstream and downstream (pond and channel) gauges. Arrows indicate channel and flow pathways for pond filling and spilling. Images correspond to gauges at each site. Top left image shows rain gauge setup.

		Halsewater	Merriott
NFM design		Offline connected storage ponds	Offline separate storage ponds
Upstream catchment area (km^2)		6.3	6
Land use		Fallow grassland	Pasture grassland
Monitoring period (months)		April 2018 – Dec 2020 (32)	Nov 2018 – Dec 2020 (25)
Mean annual rainfall (mm)		905	776
Mean annual downstream flow (mm)		357	562
Mean annual PET (mm)		528	523
Baseflow Index		0.78	0.82
Max storage capacity of ponds (m^3)	**Upstream**	608	297
	Downstream	2379	80

Table 3.1. Key characteristics for Halsewater and Merriott study sites. Upstream catchment area is calculated from the downstream gauge at each site. Land use depicts use of floodplain by the farmer. Mean annual rainfall is calculated from deployed local rain gauges as an average over 12 months. Baseflow Index refers to the proportion of baseflow in the time series (lower values indicate more flashy behaviour). Maximum storage capacity refers to the maximum volume of water that can be stored before spillage (eg. back into the channel via an outlet), based on elevation data derived from manual pond surveys.

3.3.2. Installations and field data monitoring

Field installations measured channel stage (immediately upstream and downstream of ponds); pond stage and rainfall at a 1-min resolution, from 2018-2020 (see Figure 3.1 for gauge locations). Stage was recorded using HOBO U20L-01 (Onset, 2014) water level loggers recording absolute pressure, operating at 0-207 kPa (approx. 0-9m (3000m altitude)) with a maximum accuracy error of ±0.2% FS, 2.0 cm of water (Onset, 2014). Loggers were deployed within a stilling well for protection and to dampen channel turbulence effects. Data were processed using HOBOware Pro software compensation assistant (Onset), compensating for barometric pressure. Rainfall was measured using HOBO RG3-M Data logging rain gauges (±1.0% calibration accuracy, =<2cm/hour, recording 0.2mm/tip) (Onset, 2011), supplemented with local Environment Agency gauge data to evaluate historical records.

Offline pond stage-volume relationships were quantified for each pond gauge, derived from field site and pond Digital Elevation Models (DEM's) that were produced from drone flights and detailed manual survey methods, respectively (see Figure 3.2). Drone surveys were conducted using a DJI FC350 Inspire 1 drone (images captured were 4000 x 3000 resolution, 1.56 x 1.56um pixel size), flown at a 98.9m altitude to generate a ground resolution of 1.61cm/pix. Flights were conducted during winter to reduce effects of vegetation cover (Puttock *et al.*, 2015). Ground control points (GCPs) were deployed across each site (>20, 50 x 50cm, black with white cross), at varying elevations and distances. Surveys were georeferenced using an OS total station, where markers and aerial images were processed using Structure from Motion (SfM) software, Agisoft Photoscan (version 1.4.5). Sensitivity tests revealed the optimum workflow for data processing, to reduce horizontal marker error to <10cm using camera optimisation tools. Manual surveys were conducted with an OS total station and prism pole, with >300 survey points taken in and around each pond to gain a high-resolution pond DEM. This was used to supplement drone SfM DEMs, where due to the high pond levels on certain flight days, there was low confidence in the produced pond bathymetry from SfM methods alone. An empirical relationship between monitored pond stage and DEM elevation was established, which was then applied to gain a stage-volume rating curve from a fitted power law (eqn. 1), where V = volume (m^3), a and b = coefficients and h = pond stage (m). Key volume information and threshold heights were extracted for the characterisation of dynamic interchanges between the ponds and channel (see Table 3.1).

$$V = a(h)^b \qquad \text{eqn. 1.}$$

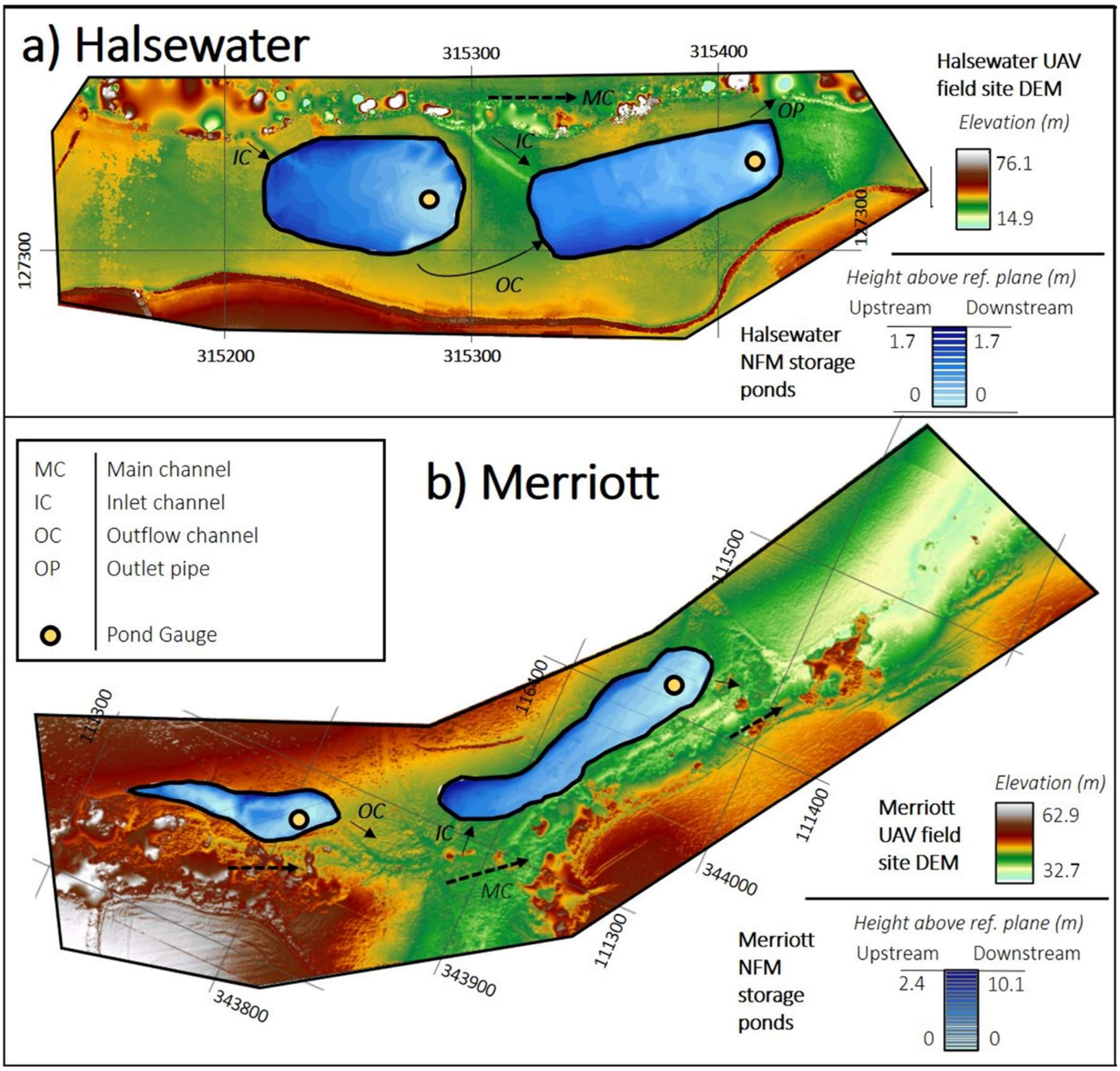

Figure 3.2. Study site DEMs produced in 2019, applying drone SfM methods. Elevation refers to metres above sea level. Pond DEMs are overlain, generated using manual measurements and illustrating height from a reference gauge (0m) for pond stage to volume conversions. Detailed are inflow/outflow features where applicable to NFM function.

Rated section flow gaugings were collected for a range of river discharges using velocity area methods (see Figure 3.1 for gauge locations). This enabled stage-discharge relationships to be derived for each channel gauge as per Nicholson *et al.* (2019). Depth and velocity measurements were collected at 10cm cross-section intervals, using a Model 801 Electromagnetic Open Channel Flow Meter (Valeport) recording a 60 second mean. Stage-discharge curves were established by fitting a power law equation (eqn. 2) through the collected stage-discharge ratings to calculate Q (m^3/s), where Q = discharge, a and b = coefficients and h = river stage (m). See Figure 3.15, for flow and volume rating curves.

$$Q = a(h)^b \qquad \text{eqn. 2.}$$

3.3.3. Rainfall event definition

Rainfall and flow data were processed using a rules-based event definition workflow, from which key metrics were systematically extracted (Figure 3.3). Firstly rainfall data were separated into events, based on a minimum inter-event (MIT) of 3 hours (Deasy *et al.*, 2014). This MIT was determined from visual examination to ensure that separate events were kept distinct, whilst acknowledging that consecutive bursts of rainfall within a small-time frame constitute a multi-peak event, where flows remain high, with no return to baseflow. Event start was identified as the first timestep of continuous rainfall and event end was defined once flow returned to pre-event baseflow (with a 10% tolerance). If event end cannot be defined this way (eg. flow does not return to pre-event flow conditions), the event was not included because complete hydrographs (5^{th}-95^{th} rising/recession limb) were required for flow volume analysis. Whilst this event definition methodology was designed specifically for these sites using MATLAB (2019b), similar approaches have been developed elsewhere in R (eg. Deasy, Titman and Quinton, 2014; Puttock *et al.*, 2017). Finally, only events with complete datasets were extracted (4.2% of the time series is missing). See chapter 3.5.6. for a list of the full rules-based event definition workflow.

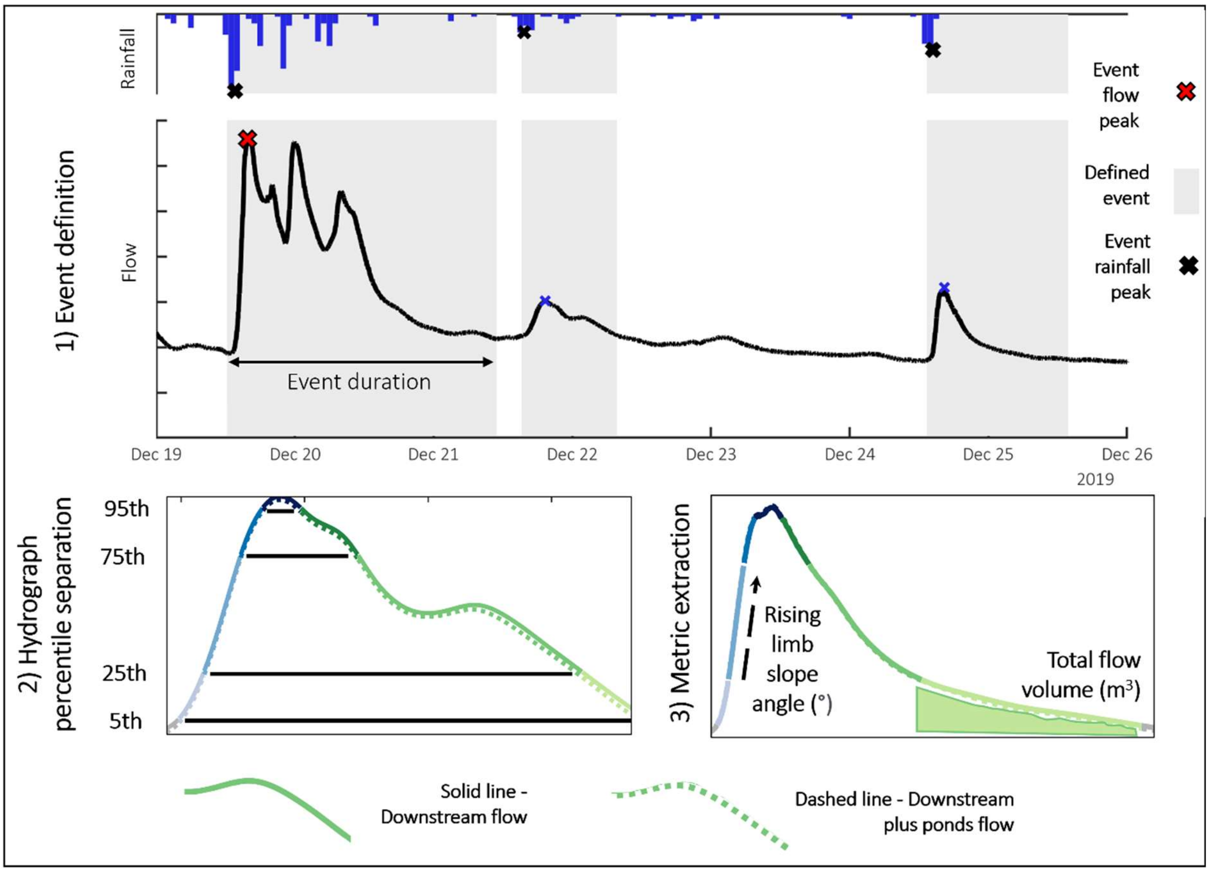

Figure 3.3. Rules-based workflow. 1) Event definition, based on separated rainfall events and flows. 2) Hydrograph separation, where the 5th, 25th, 75th and 95th percentiles for the rising and recession limb are extracted from each event. This is applied to downstream flow and downstream flow plus ponds. 3) Metric extraction details the separation of total flow for each percentile group and rising limb slope angle.

3.3.4. Structural and hydrological conditions for ponds to function

Substantial variations in rainfall and antecedent conditions occur across the defined events. These are expected to have marked implications for storm runoff coefficients, flow peaks and attenuation (Nyssen *et al.*, 2013; Puttock *et al.*, 2017). Thus, it is important to understand the hydrological thresholds required for ponds to produce high temporary storage volumes and generate downstream flow reductions. In this study, these hydrological thresholds are analysed according to the impact that event rainfall depth and antecedent conditions, have on event peaks. Antecedent conditions are calculated using an Antecedent Precipitation Index (API) (eqn. 3), which represents accumulated rainfall over a period of time. The API value increases with additional rainfall (P) and declines with each dry day, according to a decay constant (k) of 0.9. This value was selected as a commonly used value elsewhere (Heggen, 2001; Ali *et al.*, 2010).

$$API_d = kAPI_{d-1} + P_d \qquad \text{eqn. 3.}$$

Offline ponds are designed to fill directly from the channel at a given stage height via an inlet, thus connecting the floodplain directly with the channel. Flow then gradually spills back into the channel via an outlet (Nicholson *et al.*, 2012). For Halsewater, the two ponds are connected on the floodplain, where flow can travel from the upstream pond to the downstream pond, across the floodplain. For Merriott, the two ponds are separate, both with distinct inlets and outlets. To understand how these structural differences may impact on pond function, the flow and volume thresholds required for pond filling and spilling were extracted. For both sites, inlet heights were determined from discussions between FWAG-SW and the landowners, where they were constructed at the level where high flows had been typically reached during previous large winter events.

To ensure sufficient storage is available for the next event, ponds should spill adequately following a peak (Nicholson *et al.*, 2012). Complex, multi-peak events may negatively affect the functioning of ponds to attenuate peak flow if pond storage has insufficient time to spill and regain capacity for the second peak (Wilkinson *et al.*, 2010b; Metcalfe *et al.*, 2017). This is also an issue for single-peak events if they are large and long enough in duration that pond capacities are reached before the event peak. Moreover, there needs to be sufficient time in between events for pond spilling and a return to pre-event flow conditions. Multi-peak events are extracted in this study to consider in greater detail the impact fast successive filling and spilling on pond capacities, which is not clear for multi-peak events from the summary event analysis conducted here. Multi-peak events are defined as events with more than one rising and recession limb that fall <75th percentile of the event hydrograph. This threshold was selected to ensure a distinct separation between peaks to constitute a multi-peak event, whilst highlighting that a return to baseflow does not occur. These multiple rises and falls are associated with distinct bursts of rainfall. Pond storage percentage capacity values were extracted at each peak to consider if during the monitored, multi-peak events, storage capacities sufficiently coped with multiple pond fills and spills within a short time frame.

Finally, local rainfall records were utilised to place the monitored rainfall depths into context and consider the likelihood of larger events than those monitored occurring and the implications for pond function and efficacy. For Halsewater, rainfall data were sourced from a local tipping bucket rain gauge (station ID: 52100, ST064291). For Merriott, daily rainfall data were sourced from an observed gauge (Haselbury Plucknett, ST463 110). For each site, we compared the cumulative distribution of rainfall for the monitoring period (2018-2021) with a historical period (1961-2021 for Halsewater and 1971-2021 for Merriott), see Figure 3.4. Data for both sites was accessed from an EA historic data request, which was used to extract the number of historical daily rainfall values that exceeded the maximum daily rainfall recorded in the monitoring period of this study.

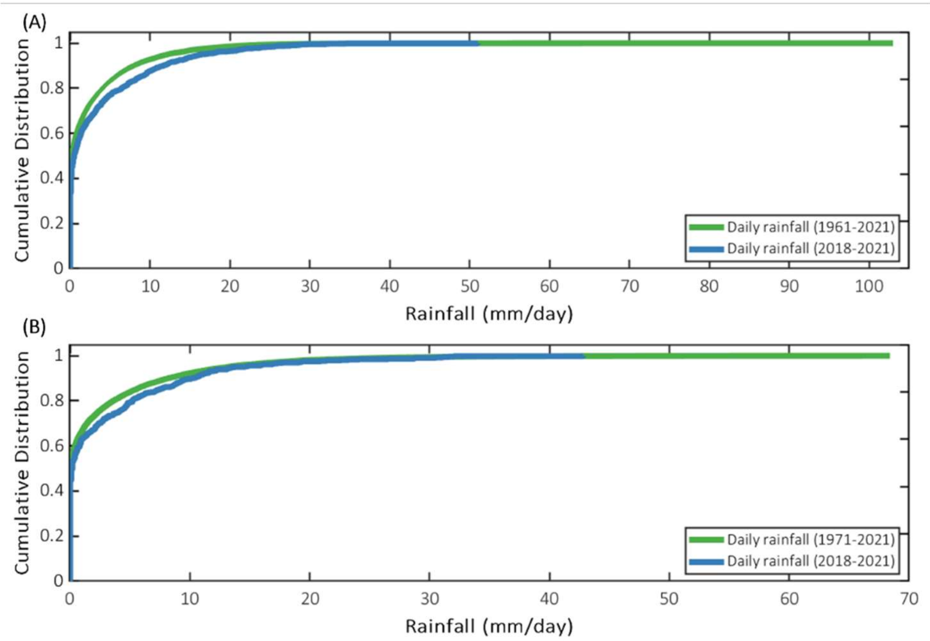

Figure 3.4. Comparison of a cumulative distribution of local historical rainfall record, with the same record but over the monitored period (2018-2021). For Halsewater (A), daily rainfall data is sourced <8km from the site, from a local gauge (ST064291). For Merriott (b), daily rainfall data is sourced <2km from the site (ST463 110).

In addition, using local historical mean daily flow data records (UKCEH, 2022), Annual Exceedance Probability (AEP) was calculated for each event through comparisons with calculated mean daily flow at Halsewater and Merriott, respectively (see figure 3.5).

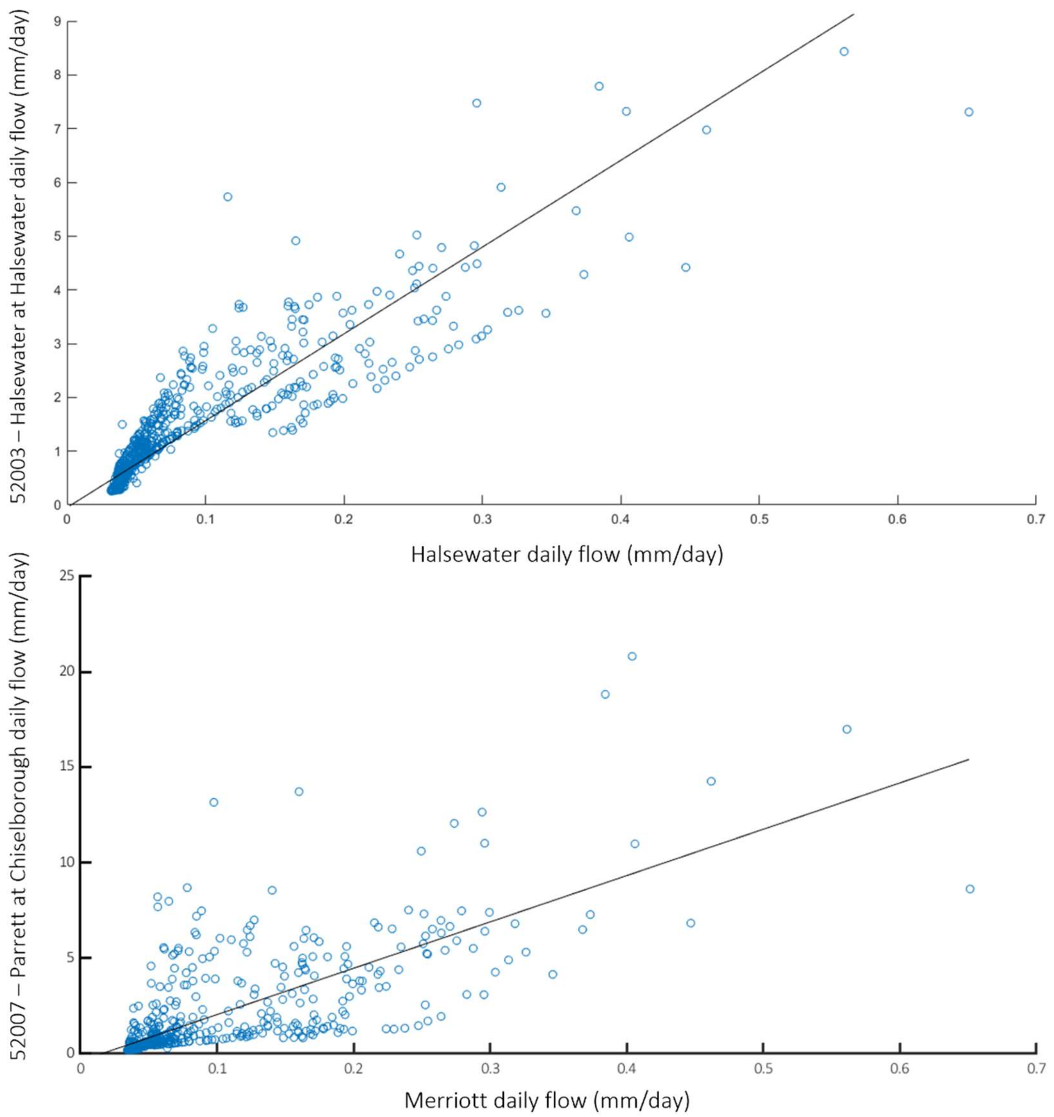

Figure 3.5. Scatter of mean daily flow to compare Halsewater and Merriott flow with a local downstream gauge. Mean daily flow at local historic gauges was subsequently used to calculate AEP for each monitored event.

3.3.5. Hydrological responses

We assessed the efficacy of ponds to dynamically store stream flow across events, by comparing two time series. Firstly, the gauge flow immediately downstream of the floodplain ponds was utilised, characterising the whole system outflow, including where ponds are filling, storing, and spilling water across events. Secondly, for each timestep, each downstream gauged flow value (m^3/s) was added to pond volume change (storage volume, converted to m^3/s), to present a scenario as if the ponds did not exist. Indeed, any increase in pond storage (for example, filling in an event) is relative storage that at a given timestamp is not contributing to downstream flow. Equally, when offline ponds are spilling back into the channel (eg. via an outlet), this represents an additional flow to the channel. Any difference between the two, time series represents the impact of offline ponds. If no change is extracted, ponds are having no impact on downstream flow, which is typically expected during baseflow periods. Through this approach, it is assumed that any change in pond volume, regardless of whether the ponds are connected to the channel (inlet thresholds are reached), has an impact on downstream flows. In this study, non-inlet filling events (where flow thresholds for pond filling from the channel are not met) are also considered as if during an event, pond volume increases as a result of rainfall, sub-surface, or surface flows, it is assumed that without this storage capture within the ponds, these volumes would impact on downstream flows.

Hydrological responses were analysed according to their efficacy for attenuating storm event water, though comparing total flow rate volumes. Analysis was conducted on all events in the top 30% magnitude. For multi-peak events, metrics were extracted from the first peak of the event. Total flow volume (m^3) was extracted across hydrograph percentiles to highlight the movement of stored water between the channel and ponds and the associated channel flow attenuation. The impact of attenuation on the rising limb was analysed by extracting the slope angle between the 25th and 75th percentiles of the rising limb for each flow dataset. These percentiles were selected to ensure the impacts of the event start and peak on slope values were negated. Where flow is removed and temporarily stored, a smoother hydrograph rising limb is anticipated with a reduction in flashiness. Finally, the highest recorded magnitude event is presented, (based on hydrograph flow rise) to consider attenuation in detail.

3.4. Results

Firstly, the monitored dataset is presented for all 4 gauges and local rainfall for the full timeseries (see Figure 3.6). In total, for Halsewater, 170 rainfall events were separated according to the event separation methodology, over a 32-month monitoring period. For Merriott, 112 rainfall events were defined: a smaller number on account of a shorter monitoring period (25-months) and lower annual rainfall values in south Somerset (Merriott) relative to west somerset (Halsewater), see Table 3.2.

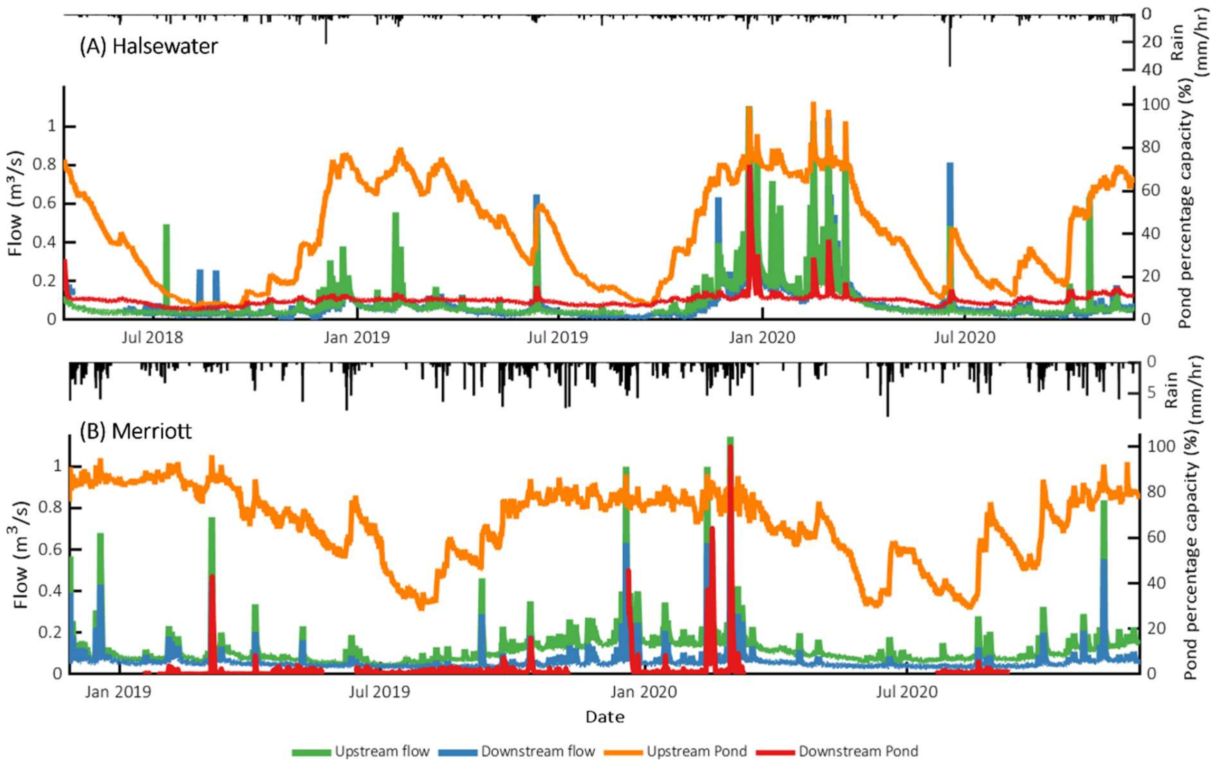

Figure 3.6. Complete time series for Halsewater (a) and Merriott (b). Presented are flow data (m^3/s) storage pond capacity (%) and rainfall (mm/hour) for both sites between April 2018 and December 2020 (for Halsewater) and November 2018 and December 2020 (for Merriott).

		Halsewater	Merriott
Total number of events extracted		170	112
Mean event rainfall (mm)		9.5	8.4
Max recorded rainfall (mm/hour)		37.4	7.4
In-channel inlet pond fill threshold (m^3/s)	**Upstream Pond**	0.75	1.3
	Downstream Pond	0.83	1.05
Number of inlet-fill events recorded	**Upstream Pond**	5	0
	Downstream Pond	5	1
Max recorded in-channel flow (m^3/s)	**Upstream**	1.1	0.75
	Downstream	1.1	1.14
Mean recorded pre-event pond storage (m^3) (% full)	**Upstream Pond**	284 (47%)	207 (70%)
	Downstream Pond	237 (10%)	1 (1%)
Max recorded pre-event pond storage (m^3) (% full)	**Upstream Pond**	494 (81%)	266 (89%)
	Downstream Pond	1051 (44%)	22 (28%)
Max recorded pond storage (m^3) (% full)	**Upstream Pond**	608 (100%)	303 (100%)
	Downstream Pond	1690 (72%)	80 (100%)
Mean recorded pond storage peak (m^3) (% full)	**Upstream Pond**	304 (50%)	223 (75%)
	Downstream Pond	269 (11%)	3 (4%)
Events analysed (top 30% of extracted)		51	29

Table 3.2. Study site storm characteristics extracted from all separated events. Where pond capacity is reached, water may spill into the connected downstream pond (Upstream Pond, Halsewater) or return to the main channel via an outlet (Halsewater and Merriott). Mean and maximum values taken from all separated event flows/volumes.

As flow attenuation and floods are the focus here, the highest 30% magnitude events were extracted for analysis, based on event hydrograph flow rise, determined as the 5^{th}–95^{th} downstream rising limb (Puttock *et al.*, 2017, 2021). Whilst this separation included both single and multi-peak events, each multi-peak event is considered to be one storm event, where there is no return to pre-event conditions and there are distinct peaks associated with a corresponding number of rainfall bursts. The highest of these two or three peaks within a multi-peak event is extracted for event analysis, in terms of the 5^{th}-95^{th} rise metrics for determining event magnitude. For Halsewater this presented 51 events for analysis. For Merriott, 5 events were omitted from analysis due to missing downstream pond data, leaving 29 events to be presented for analysis (see chapter 3.5.6. for full workflow, including criteria for event inclusion). No events were omitted for Halsewater as missing data periods did not coincide with a top 30% magnitude event. Focussing on these highest magnitude events removed those with rainfall volumes <4mm across all sites and with small channel responses, where minimal attenuation can already be assumed. This is illustrated by Figure 3.7. which shows the distribution of extracted events and the cut-off mark for those above the 30% magnitude for analysis. Across the 2019/20 winter period (December-February), up to 50% of the analysed events occurred, including all recorded inlet-filling events.

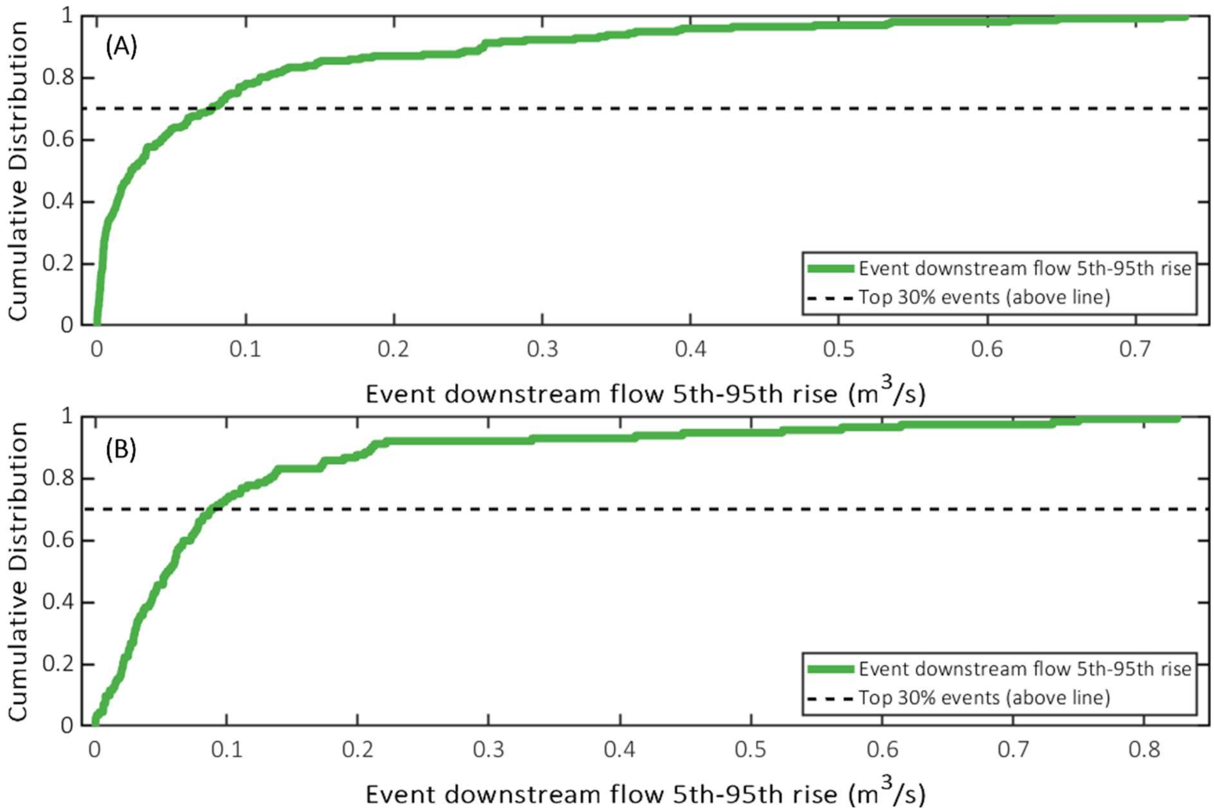

Figure 3.7. Cumulative distribution of all separated events according to their magnitude, determined by their 5th-95th downstream rise. The point of extraction of the top 30% magnitude events is indicated for Halsewater (a) and Merriott (b). This leaves 51 events for analysis for Halsewater and 29 for Merriott.

3.4.1. What is the impact of design, management, and hydrological inputs on storage pond function?

In this section, we consider the structural constraints and hydrological conditions for ponds to function. There is an overall highly variable relationship between API, event rainfall and total event volume for both sites (see Figure 3.8). Despite this variation, typically the highest API or rainfall depth values are associated with events with the highest flow rise for both sites (Figure 3.8). The highest event rainfall values are recorded by Halsewater in June (up to 53.4mm, over >16hrs), although do not present the highest flow rise values (maximum flow rise of 0.73m^3/s, associated with 13.4mm of rainfall, recorded in February). A similar pattern is presented for Merriott, although API and rainfall depth values are typically smaller (maximum 68 and 35.2mm respectively) and maximum flow rise values are higher (up to 0.83m^3/s), compared to Halsewater.

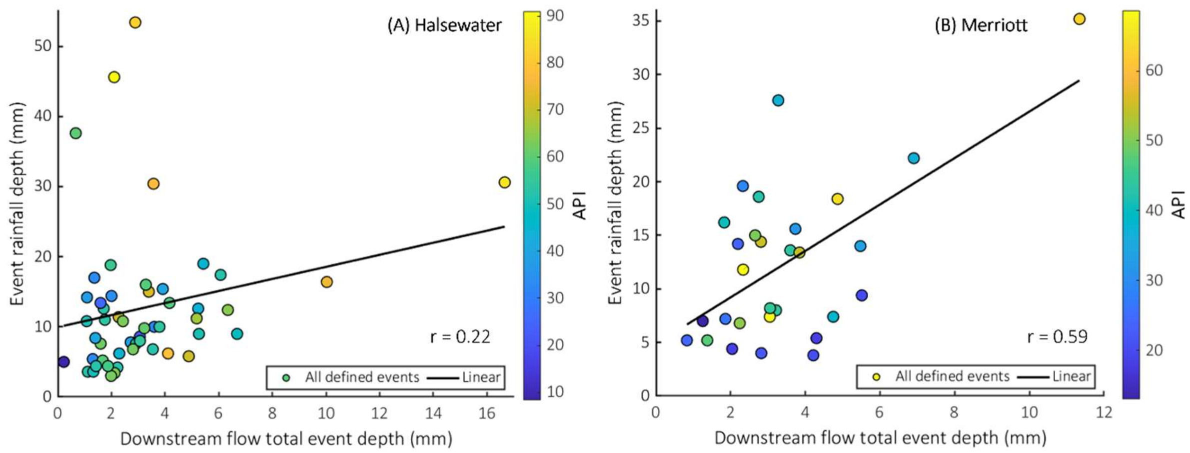

Figure 3.8. Impact of rainfall and calculated API on downstream flow total event depth for Halsewater (a) and Merriott (b). Correlation coefficient (spearman's rank) are indicated.

For Halsewater, a flow threshold of >0.75m^3/s (0.78m stage) is required to initiate pond filling, directly via an upstream inlet from the channel. This was achieved in 5 events (all occurring from December 2019-March 2020, with rainfall depths between 12.4 and 30.6mm, see Figure 3.9b). Of the 51 events analysed (top 30% magnitude), these 5 events produced the highest combined pond volume rises (271-1367m^3), whilst the remaining 44 out of 51 events produced combined volume rises from 0-252m^3. These storage increases that occurred when inlet thresholds are not met are attributed to rainfall and local overland flows from surrounding fields and small ditches. In contrast, for Merriott, downstream flow thresholds of 1.3m^3/s (1.9m stage) for the upstream pond and 1.05m^3/s (1.65m stage) for the downstream pond are required for direct filling from the channel (Figure 3.9b). Downstream pond filling was achieved by one event across the monitoring period (peak of 1.14m^3/s), whilst the upstream pond fill threshold was not reached. This one inlet-filling event produced the highest combined pond volume increase of 83m^3.

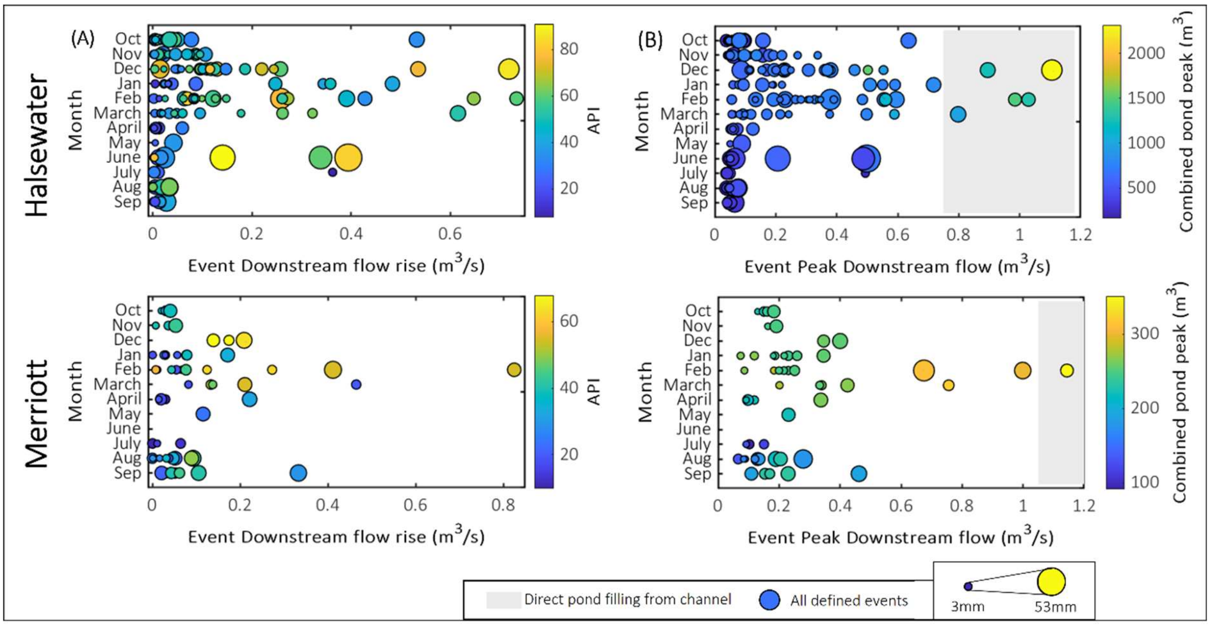

Figure 3.9. Storm, flow response and pond fill controls and required thresholds, where each scatter dot represents 1 analysed event (size proportional to event rainfall depth (mm)). (A) represents the seasonal (month), rainfall (depth) and antecedent conditions (API) controls on downstream flow rise (5th-95th percentile rate change). (B) shows the flow rate required for pond fill activation (grey shading), via inlets from the channel and the resultant combined pond peak volumes for each event. For Halsewater, pond filling occurs from 0.75m^3/s. For Merriott, upstream pond filling occurs at 1.3m^3/s (not indicated) and at 1.05m^3/s for the downstream pond. For multi-peak events, the first peak is extracted for inclusion here.

Next, the multi-peak events recorded across the monitoring period (11 for Halsewater and 4 for Merriott) were considered, to detail whether reduced storage capacity is impacted during consecutive peaks (see Figure 3.10). Multi-peak events are considered as those with >1 peak that exceeds the 75th percentile, that is associated with a corresponding number of individual rainfall bursts and no return to pre-event conditions in between peaks, which occur within the defined MIT. For Halsewater, this includes the largest recorded event, a 3-peak event (multi-peak event 6, see Figure 3.10). In this event, near maximum capacity was reached in the upstream pond at the 1st peak. Despite some spilling after the 1st peak, upstream pond storage was limited at the 2nd peak. Remaining multi peak events are lower magnitude events and have larger quantities of potential storage remaining after the 1st peak (max 80% and 40% full in the upstream and downstream pond respectively). For Merriott, no multi-peak events were recorded where near-maximum storage capacity was reached. Pond capacities were smaller in Merriott ponds, where for the downstream pond minimal (max 3%) storage change was recorded between peaks.

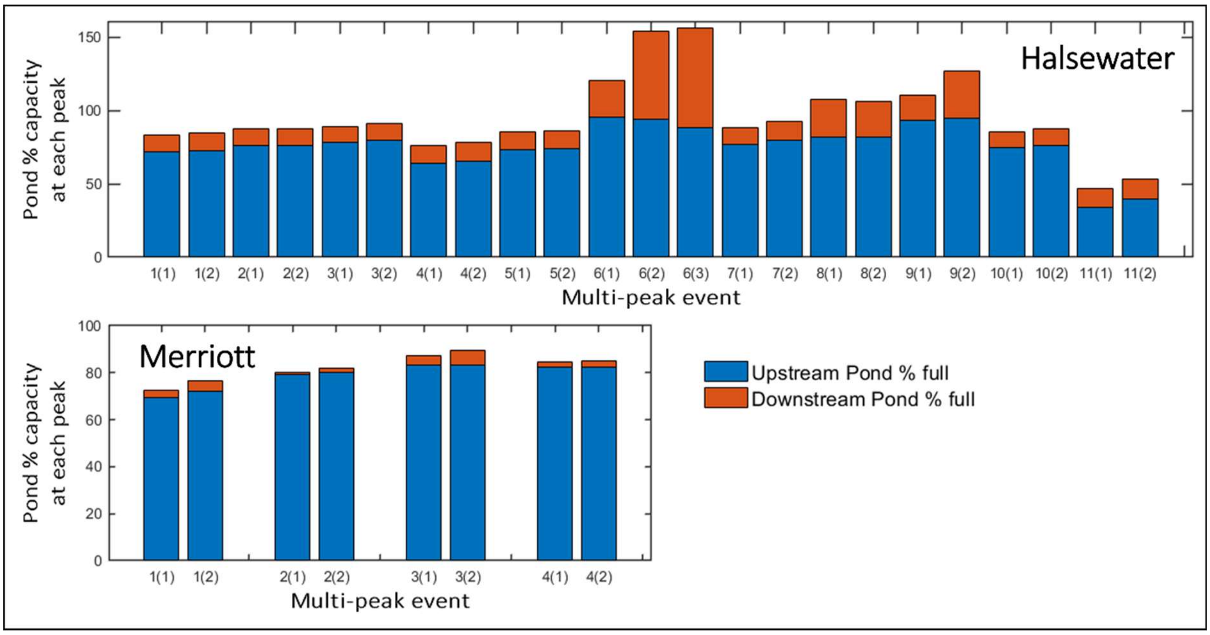

Figure 3.10. Change in pond volume storage potential across multi-peak events. Detailed is upstream and downstream storage pond percentage capacity at the 1st and 2nd event peak (according to downstream gauge) for each multi peak event (11 for Halsewater and 4 for Merriott). X-axis plotted as multi-peak event number and peak (1, 2 or 3).

3.4.2. What is the dynamic hydrological response of ponds to rainfall events?

To assess the response of ponds to rainfall events, their impact on downstream flow (Figure 3.11) and hydrograph rising limb (Figure 3.12) were analysed. The highest-magnitude event for both sites are presented (those with the highest hydrograph flow rise), in order to demonstrate the attenuation effect and efficacy of the ponds across the hydrograph (Figure 3.13).

The results show two types of pond filling, both with subsequent implications for downstream flow reductions. For both sites, this filling trend typically occurs in the rising limb of events (flow reduction), switching to a spilling (flow addition) in the recession limb. Where flow reach inlet-filling thresholds, enabling pond filling directly from the channel and temporary pond storage, the highest downstream flow reductions are presented (see square scatter boxes on Figure 3.11). For Halsewater, inlet-filling events (flows >0.75m^3/s) produce the highest reductions in total volume, with 68-408m^3 stored at event peaks (>95th percentile) and 2.3–7% reductions in downstream flow. When flow is returned to the channel, there are flow additions of up to 176m^3 (1.3%) and 417m^3 (1.6%) in the 75th-25th and 25th-5th percentiles, respectively. These events produced a reduction in hydrograph rise slope angle by up to -2.3^o, showing small reductions in hydrograph flashiness where flow is removed and temporarily stored (see Figure 3.12). In contrast to Halsewater, for Merriott, far less marked reductions in flow volume are shown, with a maximum peak reduction of 1.4% The one inlet-filling event (flows exceed 1.05m^3/s) showed the highest percentage reduction in the 5th-25th percentile of the rising limb (2.4% flow reduction), whilst volume reductions are greatest at the peak (35m^3). This produced small impacts on rising limb slope angle (maximum reduction of 0.14^o).

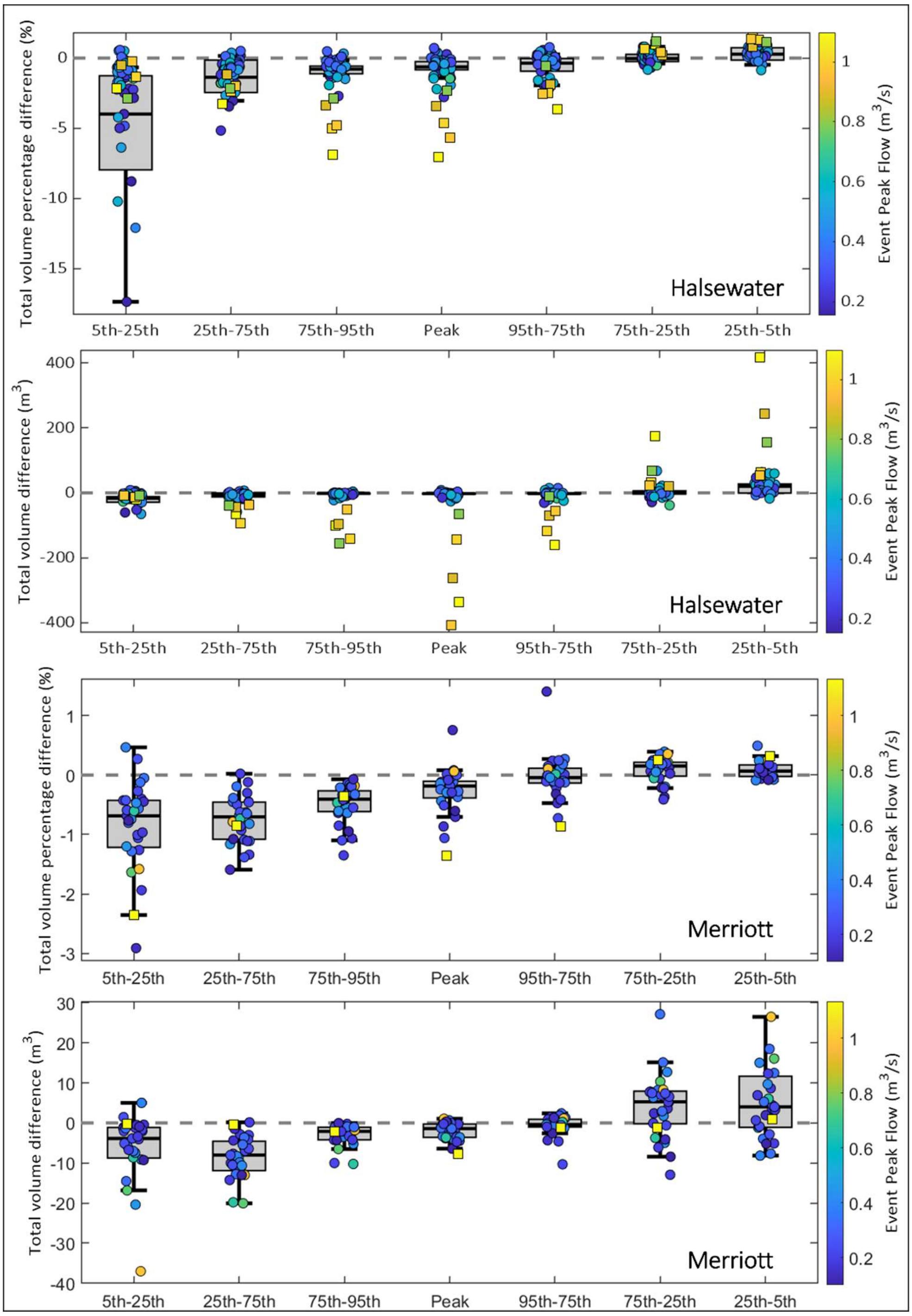

Figure 3.11. For each rainfall event (scatter), the impact of ponds on total flow volume change and percentage change is plotted as a boxplot for the rising limb, peak, and recession limb, separated into percentile groups (5th, 25th, 75th and 95th). Event peak flow is indicated by the colourbar for each scatter event. Dotted lines indicate 0 difference (no change in pond volume), with values above indicating pond spilling (addition of flow downstream) and values below indicating pond filling (reduction of flow downstream).

Pond filling also occurs, even where flow does not reach the inlet-filling thresholds, which is evident from storage increases. As these volume additions would assumingly reach the channel as runoff or subsurface flows if not intercepted and stored within the floodplain ponds, flow reductions downstream are still evident even though inlet thresholds are not reached (see circle scatters on Figure 3.11). For non-inlet filling events, the highest flow reductions occur in the 5th-25th percentile of the rising limb, producing smaller downstream flow reductions (up to 60m^3). This is accounted to the highest volume additions occurring in the early stages of these non-inlet filling events, principally from direct rainfall, and surface flows into the ponds. As a result, non-inlet filling events produced minimal impacts on rising limb slope angle (maximum reduction of -0.2° for Halsewater).

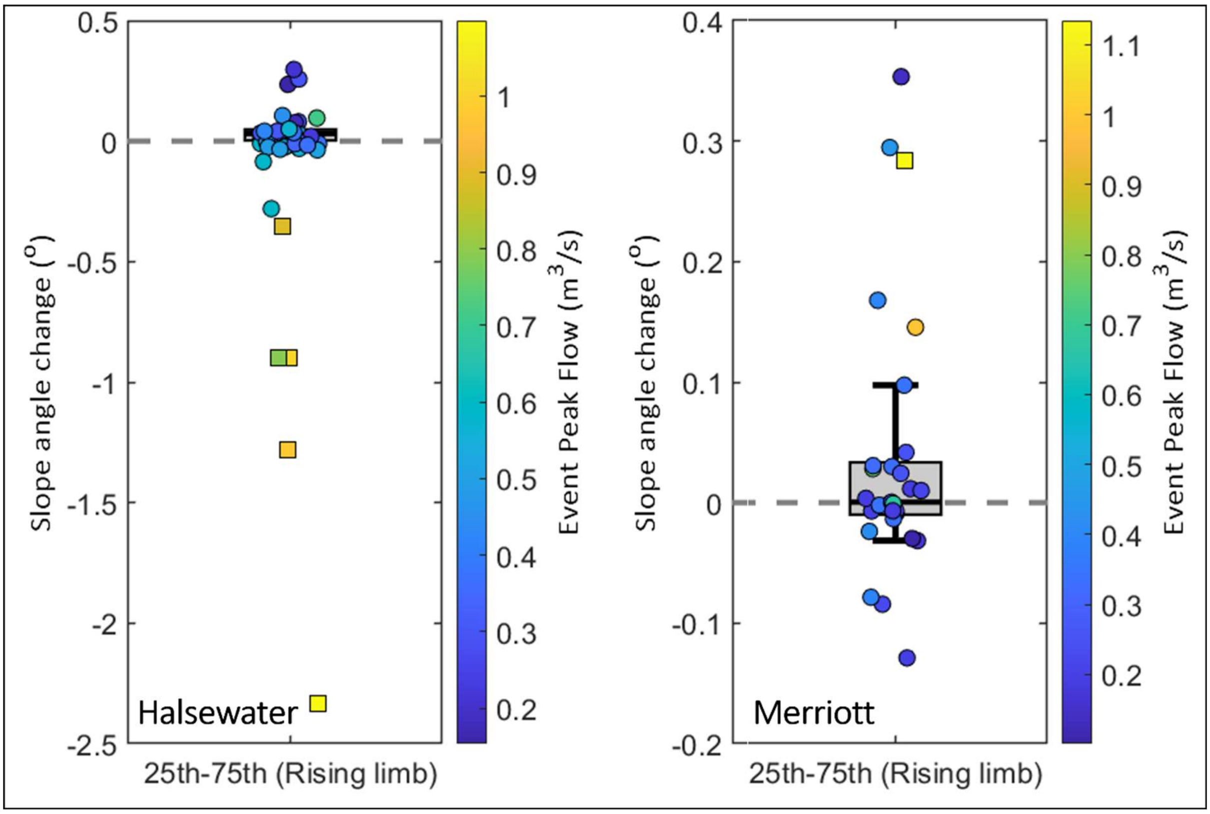

Figure 3.12. For each rainfall event (scatter), the impact of ponds on the hydrograph rising limb is plotted as a boxplot for the 25th-75th percentiles of the rising limb. Dotted lines demonstrate 0 difference in hydrograph slope, with values above indicating a rise in flashiness and values below indicating a reduction in flashiness.

Analysing higher-magnitude events in detail enables greater consideration of high attenuation potential events (see Figure 3.13). For Halsewater the largest recorded event (19th December 2019, 31% AEP) with three peak flows, shows marked attenuation at the first two peaks, with flow volume reductions of up to 8.2% (first peak) and 6.6% (second peak). These compare to the maximum 7% reduction recorded, based on percentile extraction (95th-95th), presented in Figure 3.10. Attenuation diminishes by the third peak (max 1.8% reduction), as channel flows are lower, although still exceed the inlet filling threshold. Upstream pond storage remains high throughout, increasing to 100% capacity in the first and second peak, with small (up to 20%) quantities of spilling into the channel between each peak. Downstream pond volume change is more notable, rising from 14% to 72% full in 12 hours. Despite being the largest recorded event, storage capacity is not reached, with 664m^3 still available at the second peak (equating to 22.3% of storage capacity remaining). For Merriott, the largest recorded event (29th February 2020, 41% AEP) is a single-peak, inlet-filling event. Flow reduction downstream reaches a maximum of 2.7% prior to inlet thresholds being reached in-channel. From 04:50hrs, thresholds exceed 0.92m^3/s, where then inlet filling can occur, where there is a subsequent maximum flow reduction downstream of 1.7%. Downstream pond storage increases occur as a result, from 2% to 100% within 2 hours. Downstream pond attenuation occurs principally during the channel peak, reaching capacity in the 75th percentile (recession limb), when spilling occurs. Upstream pond volumes remain high throughout (81% full at event start, to 91% at the peak).

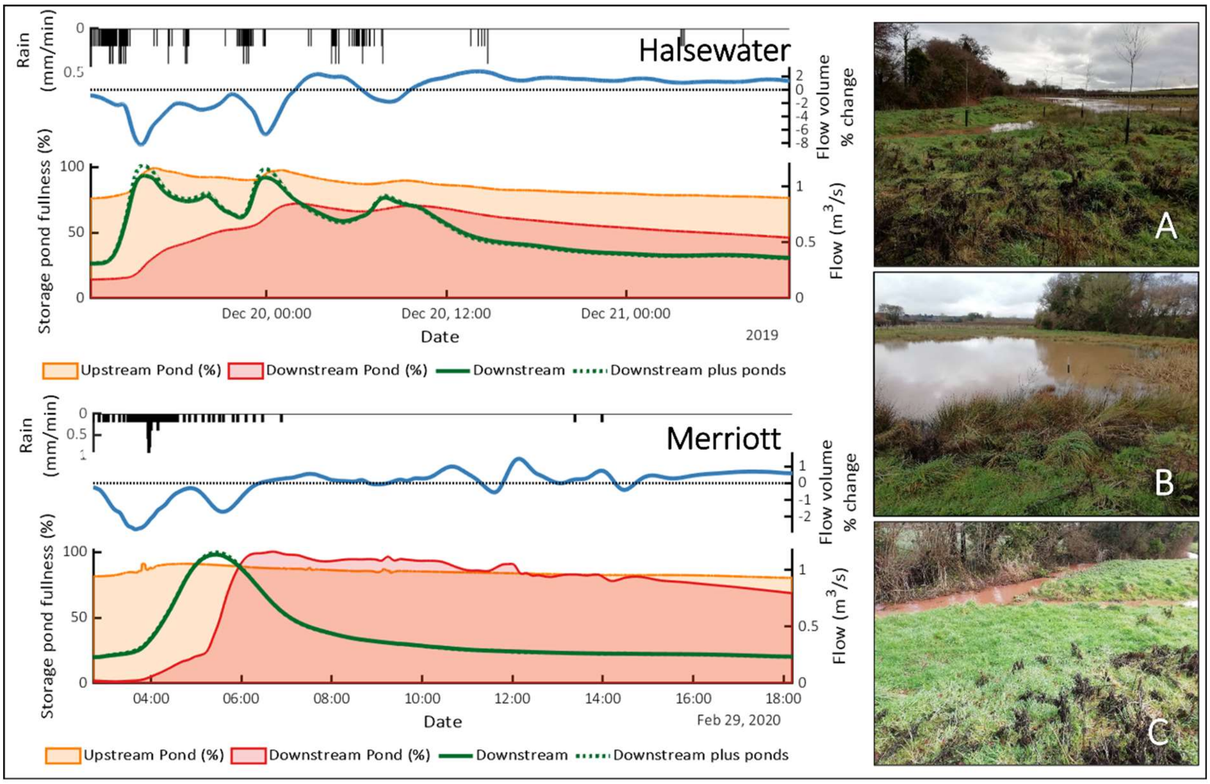

Figure 3.13. An example high-magnitude event from both study sites, detailing event rainfall (top plot), flow volume percentage change at each timestep (middle plot) and downstream flow and storage pond percentage capacity (bottom plot). Images illustrate Halsewater high channel flows generating inlet filling during (A), storage capacity of upstream pond reached (B) and downstream pond inlet filling (C) during 19th December 2019 event.

3.4. Discussion

3.5.1. Pond function is dependent on hydrological conditions and pond structure

Our results demonstrate that antecedent conditions and event rainfall volumes are strong controls on pond function during events. At both sites rainfall volumes were typically too low in the summer months to generate high magnitude (top 30%) flow events. Indeed, for Halsewater and Merriott, >48% of analysed events were extracted from the 2019/20 winter period. Daily rainfall totals over the monitored period were compared with historical values to consider whether the impacts presented over the events captured in this study, may be representative of historically typical events. This is vital to understand the likelihood of thresholds being exceeded in future events (eg. ponds overtopping and the system being overwhelmed).

Our results also show that optimal pond structures are vital for channel and pond filling and spilling dynamics if ponds are to function according to their design specifications. For inlet-filling, offline ponds require fill thresholds that are high enough for direct filling from the channel in the highest magnitude events, assuring capacity is conserved for potentially flood-scale storms (Nicholson *et al.*, 2019). This is demonstrated by Halsewater as $0.75m^3/s$ flow is required for pond filling via the inlet, which is >10x higher than mean downstream flow ($0.073m^3/s$). However, the rainfall volumes required to produce these high flows varies seasonally as whilst >12mm event rainfall totals were sufficient to generate winter inlet-filling events, >53mm rainfall events were inadequate to produce even corresponding summer flow (max $0.5m^3/s$ summer flow). This is due to higher antecedent conditions (API values) and saturated soils in the winter, which enables fast subsurface and overland flow into the channel, recognised elsewhere in attenuation-based structures (eg. Metcalfe et al., 2017; Wilkinson e*t al*., 2010). These conditions are required to produce inlet-filling where even relatively low rainfall totals can generate high flow events as a result of high pre-event flows. However, for Merriott even the largest recorded events did not produce flows high enough to cause inlet filling at the upstream pond. Historical data analysis highlighted that the monitored period was relatively wet in the context of previous years, with daily rainfall totals reaching 99.8% of previous daily rainfall totals since 1961 (see Figure 3.4). This has highlighted that rather than a need for larger magnitude events for Merriott's upstream pond to fill, there is a requirement instead for lower inlet heights to enable infrequent, high magnitude event filling or a mechanism whereby inlet threshold heights can be altered to manage appropriate inflows throughout the year. In this instance, modelling the potential impact of interventions on flows prior to construction may be beneficial to gain an idea of their effectiveness.

With reference to applicable NFM structures elsewhere, for example offline runoff attenuation features (Wilkinson *et al.*, 2010a) and offline diversion ponds (Nicholson *et al.*, 2012), it is important that ponds drain sufficiently for regular potential storage (Dadson *et al.*, 2017). If ponds reach capacity too early and there is a lack of drainage prior to subsequent events, storages may overload (Metcalfe *et al.*, 2017). Upstream pond spilling at Merriott is insufficient as pre-event storages are on average 76% full (mean across all events). The downstream pond allows far greater spilling as pre-event storages are 5% full (mean across all events). For Halsewater, sufficient downstream pond spilling is typically achieved (12% storage pre-event mean). However, draining can take up to 7 days following the highest magnitude events (Figure 3.6, Halsewater), which is far longer than reported rates elsewhere that were deemed too long. For example, offline ponds in the Belford catchment, reported by Wilkinson *et al.*, (2010) took 24 hours to empty via a leaky timber barrier. This drainage rate was later increased to 5-6 hours through barrier modifications (Nicholson *et al.*, 2012). However, it is important to note that for the Belford ponds, land is used for farming outside of flooding periods (Wilkinson *et al.*, 2010b), whilst for Halsewater, ponds are built on fallow land, meaning constant pond volumes are not an issue for landowners. A design improvement might be to build in pond drainage outlets which can be varied in terms of drainage time, to accommodate future, larger events via faster (or slower) drainage rates as required, for example as deployed at Holnicote (see Hester *et al.*, 2014).

It is also important to recognise that whilst multi-peak events were separately analysed in this study, for the impacts of successive filling on pond storage capacities, these capacities could also very feasible be reached during single-peak events if they are large and long enough. Maximum storage capacities were not reached during the monitoring period, even though upstream pond volumes were consistently high at both sites (66% and 72% pre-event capacity means at Halsewater and Merriott respectively). Nevertheless, there is a realistic likelihood of combined pond capacities being reached in future larger events as far higher rainfall extremes have been recorded locally (based on historical data since 1961). The maximum Halsewater daily rainfall during monitoring was 51mm, compared to a maximum daily value of 103mm in the historical data. For Merriott, local historical records show daily rainfall up to 25mm higher than 2018-2021.

Reflecting on this evaluation of two contrasting offline pond designs for NFM, a series of particular design specifications can be extracted as essential criteria to ensure the optimal function of these features across a full range of event sizes. Firstly, offline pond inlet heights must be low enough for occasional filling from the channel, which in this study, this was better achieved by Halsewater, whilst for Merriott was limited. Indeed, for Halsewater, direct inlet filling occurred in events with <83% AEP, whilst for Merriott direct filling only occurred in events with <41% AEP). Secondly, outlets must enable sufficient spilling following the event peak through pond draining back into the channel, to ensure adequate storage capacity for subsequent events. Indeed, ultimately outflows must increase proportionally with inflows, where it is important to recognise optimal pond functioning is likely to require considerable ongoing maintenance, where NFM design must be flexible and allow for improvements following initial construction. Monitoring flow prior to NFM construction may also be beneficial to gain estimates of the heights required for pond design, as might design of variable rate in and out flow structures.

3.5.2. Ponds deliver peak flow attenuation

Results detailing the response of ponds to rainfall events, based on their ability to reduce flow volumes (Figures 4.11) and hydrograph slope (Figure 3.12) have revealed their attenuating impact on downstream flow (Figure 3.13).

The two offline pond sites demonstrate that inlet-filling can occur in the highest magnitude events, where ponds successfully attenuate flows, reducing overall hydrograph flashiness. It is important to note that inlet-filling occurred in a small number of events across the monitoring period (five for Halsewater's upstream and downstream ponds, for events with a <83% AEP, one for Merriott's downstream pond, for an event with a 41% AEP, and none for

Merriott's upstream pond). However, ponds were still seen to reduce downstream flows even when these inlet thresholds were not reached as ponds filled and temporarily stored flow from other local sources. Attenuation was markedly highest during these few inlet-filling events, with peak flow reductions of up 7%, representing 408m^3 of flow (Halsewater's 19th December event, Figure 3.13, 31% AEP). The removal of channel flow for temporary storage within floodplain ponds corresponds with lower flashiness expressed as small reductions in hydrograph rising limb slope. In comparison to Halsewater, pond attenuation at Merriott is considerably smaller, with a maximum 1.4% peak flow reduction or 35m^3 of flow (29th February event, 41% AEP). Whilst smaller rainfall volumes and lower antecedent conditions are reported for Merriott in comparison to Halsewater, the high inlet heights are likely the greatest limitation on pond filling. Attenuation from offline ponds can be directly related to the quantity of pond filling and storing, as well as overall storage capacities, ultimately determined by pond inlet thresholds and rainfall volumes. Determining attenuation based on volume stored, is advantageous to gain an understanding of lag and system travel time (eg. Thomas and Nisbet, 2007; Evrard *et al.*, 2008; Wilkinson, Quinn and Welton, 2010; Puttock *et al.*, 2017). Indeed, travel time increases of up to 15 minutes due to storage were reported by Wilkinson, Quinn and Welton (2010). However, defining peaks, especially for low flow events, can be uncertain (Wilkinson *et al.*, 2010b) and extracting lag times requires detailed knowledge of catchment rainfall to gain accurate peak rainfall values. In this study, ponds were analysed as individual functions, where monitoring was installed to capture full pond behaviour (dynamic volume changes) to be tied to downstream flow responses across events (Burgess-Gamble *et al.*, 2018). Therefore, all system volume and consequently slope changes are attributed to flow attenuation and thus temporary storage on the floodplain.

Splitting events into hydrograph percentiles has highlighted the ability of offline ponds to reduce peak flow during inlet-filling events, ensuring direct filling as channel flow rises, and returning flow to the channel in the latter part of the recession limb. During non-inlet filling events, ponds had a greater impact on the earlier stages of events when local storage additions were highest. For inlet-filling events, the highest storage increases occurred once inlet-thresholds were met, which typically coincided with the event peak. In comparison to similar structures monitored elsewhere, these ponds manage high-magnitude events well, as they importantly reduce the event peak. In Nicholson *et al.*, (2019), ponds demonstrate attenuation impacts on the event rising limbs, but in high magnitude events this is diminished due to storage capacity being reached prior to the peak. A smaller event in Nicholson *et al.*, (2019) showed stronger peak flow attenuation, reducing peak flows by 12%. In contrast, in this study both study sites demonstrated limited attenuation in smaller magnitude events as flows are not high enough to generate inlet filling. Therefore, these sites highlight that this design of features is most effective within a specific range of flows.

Whilst this study has taken two typical offline storage pond designs and compared them in terms of their function and efficacy for attenuation, future studies may incorporate further design types and how they are projected to work, along with alternative inlet or outlet designs or the impact of incorporating a greater number of ponds within a system (eg. a longer chain of ponds as modelled by Nicholson et al. (2019). This research has highlighted the importance of offline pond inlet heights allowing sufficient, occasional filling, as well as enough spilling to allow for storage capacities in subsequent events. Future monitoring should also assess the efficacy of ponds following improvements to design, for example the optimisation of pond inlet and outlet heights.

3.5. Conclusions

The results presented in this study are a contribution to the empirical knowledge base of NFM installations and their efficacy. We show how two designs of offline storage ponds function in response to rainfall events and their attenuating impact on downstream flows, based on their dynamic filling, storing, and spilling capabilities.

The comparison of two sites in this study: Halsewater and Merriott, has firstly highlighted the importance of pond design to enable effective functioning and thus peak flow attenuation. Both sites demonstrated the ability to fill in event rising limbs, notably at the event peak, reducing overall hydrograph height and flashiness. However, of the two sites, Halsewater demonstrated markedly higher levels of attenuation (up to 7% downstream peak flow reduction, for a 31% AEP event). The higher channel filling threshold heights at Merriott were noted contributors to the lower levels of attenuation here (maximum of 1.4% downstream peak flow reduction), where direct inlet-filling only occurred in events with <41% AEP. Pond spilling following the event peak is particularly slow for both sites, which may pose future issues if events of a higher magnitude than those monitored here were to occur in quick succession. For the majority of events monitored at both sites, filling occurred exclusively from rainfall or storm-based surface runoff, as channel stage height was not high enough to reach inlet levels. Whilst this did produce some peak flow attenuation (maximum of 2.1% for Halsewater, for an 85% AEP event), these events typically had the greatest impact on the earlier stages of events.

These results are more broadly applicable to local understanding of features deployed in lowland agricultural landscapes and to aid future NFM design, whilst contributing to a wider evidence base for future NFM policy and implementation. Alone, single infrastructure offline storage ponds are unlikely to produce considerable reductions in flood hazard, even immediately downstream (as monitored here) due to their size, floodplain location and natural design. However, results in this study highlight they can contribute to small peak flow storage in catchment headwaters, utilising unused farmland, where opportunistic to do so. The construction of similar storage ponds in greater concentrations across small watersheds above communities at risk may provide a substantial quantity of natural flood storage in the future, with larger flood impact benefits. For the optimisation of future NFM water storage ponds, they must enable occasional filling and sufficient spilling following events, achievable through careful design and improvements following construction. As well as presenting effective, local flow storage, these results may be applicable for use as observational data in future modelling applications, to understand the impact of floodplain-based features for flood risk at the catchment scale.

3.6. Appendix

3.6.1. Halsewater

This appendix presents the dates and key metrics of 51 analysed events for Halsewater, where ERD = Event rainfall depth (mm), EP = Event peak (m^3/s), ER = Event rise (m3/s), ED = Event duration (presented as hours: minutes).

			Downstream flow		Upstream pond		Downstream Pond	
Date	**ERD (mm)**	**ED (hrs)**	**ER (m^3/s)**	**EP (m^3/s)**	**ER (m^3/s)**	**EP (m^3/s)**	**ER (m^3/s)**	**EP (m^3/s)**
12/07/18	5	00:09	21.75	29.64	3.38	78.99	4.75	138.95
27/11/18	14.2	05:11	6.34	9.45	34.01	257.99	35.03	246.87
01/12/18	10.8	04:27	6.53	10.22	31.75	328.17	23.33	260.68
07/12/18	11.4	06:32	13.17	18.46	33.59	421.26	34.84	275.40
08/12/18	15	15:53	7.73	13.71	28.17	452.84	31.65	288.25
15/12/18	12.6	08:16	7.02	11.72	31.31	439.91	29.07	255.95
18/12/18	16	08:13	15.42	22.78	27.57	470.76	42.88	279.58
19/12/18	10.8	11:50	5.73	13.52	11.33	468.56	14.83	273.06
23/12/18	7.6	04:39	5.74	13.83	11.06	462.31	15.34	254.83
18/01/19	13.4	02:04	5.19	9.38	35.38	402.15	27.60	250.10
04/02/19	14.4	05:13	25.67	33.33	30.86	464.34	61.01	297.99
06/02/19	18.8	09:23	7.28	13.88	12.87	480.35	19.55	257.19
08/02/19	30.4	21:01	15.48	22.74	24.93	487.29	39.72	279.48
12/03/19	8.4	03:15	5.70	10.26	22.27	443.06	20.06	249.55
10/06/19	53.4	16:10	23.65	29.95	100.60	314.99	151.83	373.76
02/11/19	11	11:57	5.17	10.76	23.13	311.44	27.99	292.31
14/11/19	6.8	08:44	5.36	13.22	16.82	401.71	21.29	294.78
23/11/19	4.2	05:15	5.69	20.26	3.50	443.53	4.43	322.26
08/12/19	10	09:58	8.82	21.73	21.45	421.48	25.93	275.87
12/12/19	6.2	07:04	6.01	22.79	9.93	453.15	17.95	290.35
13/12/19	10	07:28	7.48	22.15	10.38	458.09	20.12	298.70

14/12/19	9	05:28	11.15	27.52	11.20	468.71	42.12	339.66
19/12/19	30.6	19:30	43.09	66.32	128.23	603.58	1238.34	1715.24
21/12/19	6.2	10:32	6.91	30.13	4.39	474.60	0.00	1052.23
24/12/19	5.8	01:43	14.63	33.20	16.32	466.95	5.65	452.42
26/12/19	16.4	07:51	32.10	53.71	68.13	525.29	409.97	726.51
09/01/20	15.4	06:43	28.99	43.06	47.22	484.34	69.35	327.31
13/01/20	7.8	01:59	20.60	33.04	22.94	464.72	30.42	277.23
14/01/20	12.6	10:32	14.82	30.55	26.71	484.97	51.15	316.56
16/01/20	9	06:06	21.48	35.47	17.13	472.53	31.58	290.73
02/02/20	8.6	04:51	4.96	13.78	13.04	424.27	15.59	250.97
10/02/20	5.4	03:10	4.85	15.92	9.57	426.05	3.94	273.39
13/02/20	19	10:34	23.45	35.70	72.34	501.96	56.87	302.74
14/02/20	5.2	07:05	7.57	19.65	6.43	464.02	10.60	269.45
15/02/20	13.4	04:40	44.01	61.73	144.33	617.18	380.97	689.79
16/02/20	11.2	11:36	16.31	33.60	6.04	501.27	0.00	633.28
17/02/20	3.4	03:35	5.04	20.46	0.00	471.24	0.00	454.95
18/02/20	3	04:00	5.93	20.83	4.08	460.30	0.00	309.10
20/02/20	4.4	02:25	8.88	23.44	9.41	456.03	11.95	263.42
24/02/20	7.6	03:09	15.62	29.07	19.81	456.89	24.96	275.21
25/02/20	3.6	05:24	5.24	18.35	6.11	455.64	7.08	263.28
25/02/20	3.6	05:02	5.02	18.69	4.33	456.31	3.13	264.48
27/02/20	8	15:65	15.65	29.05	14.32	460.02	23.78	274.97
28/02/20	12.4	38:84	38.84	59.07	124.19	594.18	558.32	888.44
01/03/20	6.8	19:31	19.31	35.35	32.64	493.32	9.37	538.88
05/03/20	9.8	15:68	15.68	29.89	18.62	465.98	31.28	286.06
08/03/20	4.4	10:66	10.66	22.62	6.65	453.32	9.34	256.37
15/03/20	17.4	36:92	36.92	47.89	119.76	561.76	151.19	412.28
17/06/20	37.6	20:29	20.29	29.24	73.85	165.30	63.49	259.64
18/06/20	45.6	08:42	8.42	12.41	87.76	259.74	79.24	335.70
21/10/20	17	31:14	31.94	38.14	58.99	361.18	72.85	322.04

3.6.2. Merriott

This appendix presents the dates and key metrics of 29 analysed events for Merriott, where ERD = Event rainfall depth (mm), EP = Event peak (m^3/s), ER = Event rise (m3/s), ED = Event duration (presented as hours: minutes).

			Downstream flow		Upstream pond		Downstream Pond	
Date	**ERD (mm)**	**ED (hrs)**	**ER (m^3/s)**	**EP (m^3/s)**	**ER (m^3/s)**	**EP (m^3/s)**	**ER (m^3/s)**	**EP (m^3/s)**
09/02/19	4	09:23	4.01	11.00	9.92	279.65	1.51	1.81
05/03/19	9.4	08:35	34.15	45.37	27.84	287.91	30.13	34.24
12/03/19	4.4	02:32	4.93	12.08	16.05	275.20	1.27	1.94
04/04/19	15.6	09:23	13.30	20.22	25.10	257.11	5.69	6.52
08/05/19	14.2	04:31	6.94	13.86	13.22	220.06	1.22	1.57
09/09/19	19.6	10:44	19.97	27.71	42.13	189.42	0.32	0.50
23/09/19	5.2	08:45	3.76	9.26	14.26	196.01	0.47	1.13
24/09/19	16.2	06:16	6.32	13.78	33.88	229.20	4.59	5.89
30/09/19	8	03:58	3.70	10.17	14.61	230.61	1.63	2.45
06/11/19	13.6	02:29	3.19	11.47	7.66	246.58	1.21	2.21
20/12/19	11.8	06:04	8.34	20.77	8.62	230.69	6.76	29.02
21/12/19	7.4	03:40	10.47	23.46	24.86	248.71	2.00	22.67
26/12/19	18.4	06:51	12.54	24.01	13.77	247.25	5.64	7.02
13/01/20	7.2	04:42	4.67	13.82	14.30	242.09	0.73	2.02
14/01/20	14	16:38	10.29	20.76	14.08	249.38	4.89	6.55
16/01/20	7.4	06:50	4.73	15.55	13.33	246.55	1.04	2.19
27/01/20	3.8	01:19	3.40	13.00	9.81	243.56	1.04	1.98
09/02/20	5.4	07:34	3.27	13.82	26.79	244.82	0.00	1.14
12/02/20	22.2	13:49	44.99	59.93	41.14	270.58	25.60	29.59
14/02/20	35.2	38:35	24.71	38.70	21.70	253.65	41.65	50.72
27/02/20	8.2	07:39	4.59	15.07	14.25	247.60	0.15	1.74
29/02/20	13.4	04:10	49.50	68.63	12.88	271.41	70.75	80.21
01/03/20	6.8	02:42	7.99	20.38	10.26	246.88	0.00	14.59

05/03/20	14.4	05:19	12.65	25.46	20.24	260.20	5.92	7.28
08/03/20	5.2	01:37	8.25	19.99	14.78	250.25	1.52	2.74
25/07/20	7	04:33	3.86	9.03	7.91	116.66	0.59	1.35
19/08/20	27.6	18:30	10.39	10.07	58.68	171.98	3.28	2.61
24/08/20	18.6	10:17	5.56	11.37	43.30	214.64	1.30	2.23
27/08/20	15	04:33	5.35	12.29	19.74	225.79	1.38	2.22

4. Leaky woody dams for in-channel peak flow attenuation and Natural Flood Management

4.1. Context

Research question 2: What is the impact of leaky woody dams for in-channel peak flow attenuation?

Evidence for the impact of leaky woody dams for Natural Flood Management (NFM) is currently highly uncertain and constrained by a limited quantity of datasets. Empirical studies that examine the role and effects of leaky woody dams on flow are needed to critically evaluate their effectiveness for slowing and storing flow. This research chapter uses the event separation methodology introduced in chapters 2 and 3 to analyse the impact of leaky woody dams on two river reaches in the Tone catchment, Somerset. This chapter aims to evaluate the impact of leaky woody dams on downstream flows, considering changes to the rising and recession limb, and peak flow as a result of the interventions. This was examined across higher-magnitude rainfall events, extracting metrics that consider flow timing and storing quantities upstream (control) and downstream of leaky woody dams. This chapter has produced new datasets that have detailed the response of channel flow to rainfall events by comparing control sections of channel with and without leaky woody dams. This chapter aims to improve our understanding of the impact of leaky woody dam, provide case study examples and quantifiable data to inform scientists and stakeholders working on NFM.

4.2. Introduction

In natural, forested river catchments, in-channel wood accumulations are a dominant feature, arising from trees falling into the channel as a result of bank erosion, transport downstream of tree material or beaver construction (SEPA, 2015; Martin *et al.*, 2018). These in-channel wood accumulations can have wide benefits for local channel morphology, maintaining floodplain connection, increasing channel roughness and creating diverse habitats (Linstead and Gurnell, 1999; Abbe and Montgomery, 2003; Gurnell *et al.*, 2005; Osei *et al.*, 2015). However, historic human management of rivers and woodlands has resulted in the removal of forested floodplains and clearance of in-channel wood (Gippel *et al.*, 1996; Gurnell *et al.*, 2019). This has been typically carried out to expand space for agriculture, increase channel capacity and efficiency, improve navigation and reduce local flood risk and channel blockages downstream (Shields and Gippel, 1995; Thomas and Nisbet, 2012). Although these management practices have purpose in certain circumstances (eg. to avoid blockage in urbanised areas), their negative implications for flood risk downstream are now widely recognised (Dadson *et al.*, 2017; Dixon *et al.*, 2019).

There has been a marked change in public and policy perceptions and responses to in-channel wood accumulations in recent years, as demonstrated through expanding river restoration projects globally (Ruiz-Villanueva *et al.*, 2013). A shift towards catchment-based flood risk management has seen increasingly widespread deployment of artificial large wood in river channels, as one of the most common forms of river restoration and more recently, NFM (Manners and Doyle, 2008; Dixon *et al.*, 2019; Lo *et al.*, 2021). Also referred to as wood jams, leaky barriers, engineered log jams or large woody debris, these structures are typically deployed to emulate natural forested channel processes but unlike naturally occurring wood can be implemented in chosen, preferred locations (Ngai *et al.*, 2017; Follett *et al.*, 2021). Whilst their design specifications vary widely, the deployment of leaky woody dams typically involves the introduction of large (>1m in length), natural wood barriers in the channel (Deane *et al.*, 2021). They may be fixed in place to reduce the risk of large wood movement and the subsequent potential blockage of instream structures, such as bridges or culverts (Follett *et al.*, 2021). Over time they should increase stream bed heterogeneity by building up smaller debris and tree matter, increasing roughness, generating varying channel depths and velocities, whilst being ‘leaky’ enough to allow baseflow to travel through or underneath the dam unimpeded (Short *et al.*, 2019; Lo *et al.*, 2021). By enhancing floodplain connectivity and in-channel storage, leaky woody dams are expected to have a wide range of implications for NFM in terms of their hydrological, hydraulic, geomorphological and ecological impacts (Grabowski *et al.*, 2019). This is attributed to the enhancement of floodplain connectivity and generation of a range of in-channel storage, for instance as categorised by Lo *et al.*, (2021) to include underflow pools, downstream plunge pools and deflector pools.

To date, artificially deployed leaky woody dams (eg. for river restoration or NFM purposes) have been most commonly assessed using modelling techniques (Thomas and Nisbet, 2012; Dixon *et al.*, 2016; Metcalfe *et al.*, 2017; Ferguson and Fenner, 2020a; Leakey *et al.*, 2020; Follett *et al.*, 2021). Overall, evidence is increasingly showing that leaky woody dams can attenuate downstream peak flows. This has been highlighted through increases in peak travel time (Kitts, 2010; Thomas and Nisbet, 2012), reductions in peak magnitude (Odoni and Lane, 2010; Dixon *et al.*, 2016; Ferguson and Fenner, 2020a; Norbury *et al.*, 2021) and stage height (Short *et al.*, 2019), and a lengthening of the hydrograph peak and overall event duration (Dixon *et al.*, 2016). Nevertheless, current evidence is very variable. No marked flood attenuation was reported by Thomas and Nisbet, (2012) in a 1% AEP modelled event, despite reporting a peak flow delay by up to 15 minutes. Elsewhere highly variable impacts are reported, despite overall reductions in peak flow reported as a result of leaky woody dam deployment or inclusion within simulations (Dixon, 2013; Norbury *et al.*, 2021). For example, event flow peak changes between +6% and -6% were reported by Dixon et al. (2016) and changes between +124.8% and -11.4% by Norbury *et al.*,(2021), downstream of leaky woody dams.

Current evidence for the impact of artificially placed leaky woody dams is based on a very small pool of studies. Future advances in modelling applications require further empirical datasets that present numerical values that can be used to characterise the hydrological mechanisms associated with leaky woody dams and thus can examine their impacts in the field (SEPA, 2015). There is a large quantity of both modelled and empirical studies that have assessed the benefits of existing, naturally occurring large wood in channels (Gregory *et al.*, 1985; Braudrick and Grant, 2001; Mazzorana *et al.*, 2011; Deonie *et al.*, 2014; Klaar *et al.*, 2020). However, artificially deployed leaky woody dams are unlikely to have the same shape and density and therefore behaviour as natural wood accumulations, and they also tend to be secured in place unlike natural in-channel wood (Ngai *et al.*, 2017; Muhawenimana *et al.*, 2021). Therefore, data and evidence currently available that has studied the impacts of natural in-channel wood cannot be directly or immediately applied to artificial leaky woody dams and further research is required specific to newly deployed structures. The production of new datasets will be important observational data for future catchment-scale assessments of leaky woody dams, for instance to calibrate and validate model simulations. In addition, on a local level, evidence from current projects is important to detail the small-scale impacts, and to secure and optimise future NFM schemes.

Therefore, in this chapter, the impacts of leaky woody dams for peak flow attenuation, for a range of rainfall events were analysed in a headwater of the River Tone, West Somerset. This chapter aims to directly compliment additional emerging empirical datasets that are quantifying the impacts of leaky woody dams in UK catchments elsewhere, for example Norbury *et al.*, (2021) who assessed the impact of interventions for peak flow reductions in a headwater of the River Irwell, NW England. In this study, two separate sections of leaky woody dams were studied, established in January and November 2018 respectively, deployed through the Hills to Levels project (see chapter 2.2 for details). The impacts of leaky woody dams were studied using a control versus NFM experimental design, where flow was monitored immediately upstream and downstream of two sections of leaky woody dams in the same river channel. Event rainfall and antecedent conditions (quantified as an API value) were examined as key controls on event flow rise and peak. In addition, the impact of leaky woody dams across event hydrographs and for key hydrological metrics were evaluated, providing new empirical evidence on the impacts of leaky woody dams for in-channel peak flow attenuation and Natural Flood Management.

4.3. Data and methods

4.3.1 Installations and field data monitoring

Hydrological monitoring was established between January 2019 and December 2020, in an upper headwater valley site in Somerset, SW-England (upstream catchment area of 1.1km^2). The site has a mean annual rainfall of 1300mm and has a grassland (dairy farming) local land use, with a wooded river channel. Two separate stretches of leaky woody dams have been established along a river channel at this site since 2018, through the Hills to Levels project (see Figure 4.1). These were deployed to contribute to a wider scheme aiming to slow and store flow in headwater catchments in Somerset (see chapter 2.2 for details). Separating each leaky woody dam section is a 'control' section of channel (no leaky woody dams).

Monitoring comprised of firstly, an upstream study section: 'Upper Marcombe Lake', consisting of a 130m control channel section (no leaky woody dams), followed by a 120m section with 8 leaky woody dams (constructed in November 2018). This upstream study section was dominated by steep bank sides. The downstream study section: 'Lower Marcombe Lake', comprised of a further 240m control channel section (no leaky woody dams), followed by a 120m section with 5 debris dams (constructed in January 2018). This section has gentle channel banks and a wooded floodplain. Whilst there are no additional channel inputs within each study section, two small valley channels and a field drain add flows into the main channel between gauges 2 and 3 (see Figure 4.1). Therefore, higher flows are expected for Lower Marcombe Lake, compared to Upper Marcombe Lake and as a result the two study sections are not directly compared. Within the two study sections: Upper Marcombe Lake (gauges 1 and 2) and Lower Marcombe Lake (gauges 3 and 4), total flows over longer time periods are expected to match (mass balance). A schematic of the study site, including both study sections and the locations of leaky woody dams is shown by Figure 4.1.

Installations were carried out following the methodology defined in chapter 2.5. Briefly and to detail information specific to this site, stage was recorded immediately downstream of each control or leaky woody dam section for the Upper Marcombe Lake and Lower Marcombe Lake study sections. Stage was recorded using HOBO U20L-01 (Onset, 2014) water level loggers. Rainfall data were retrieved from a local EA rain gauge (station id. 45168) due to its proximity (distance <1km).

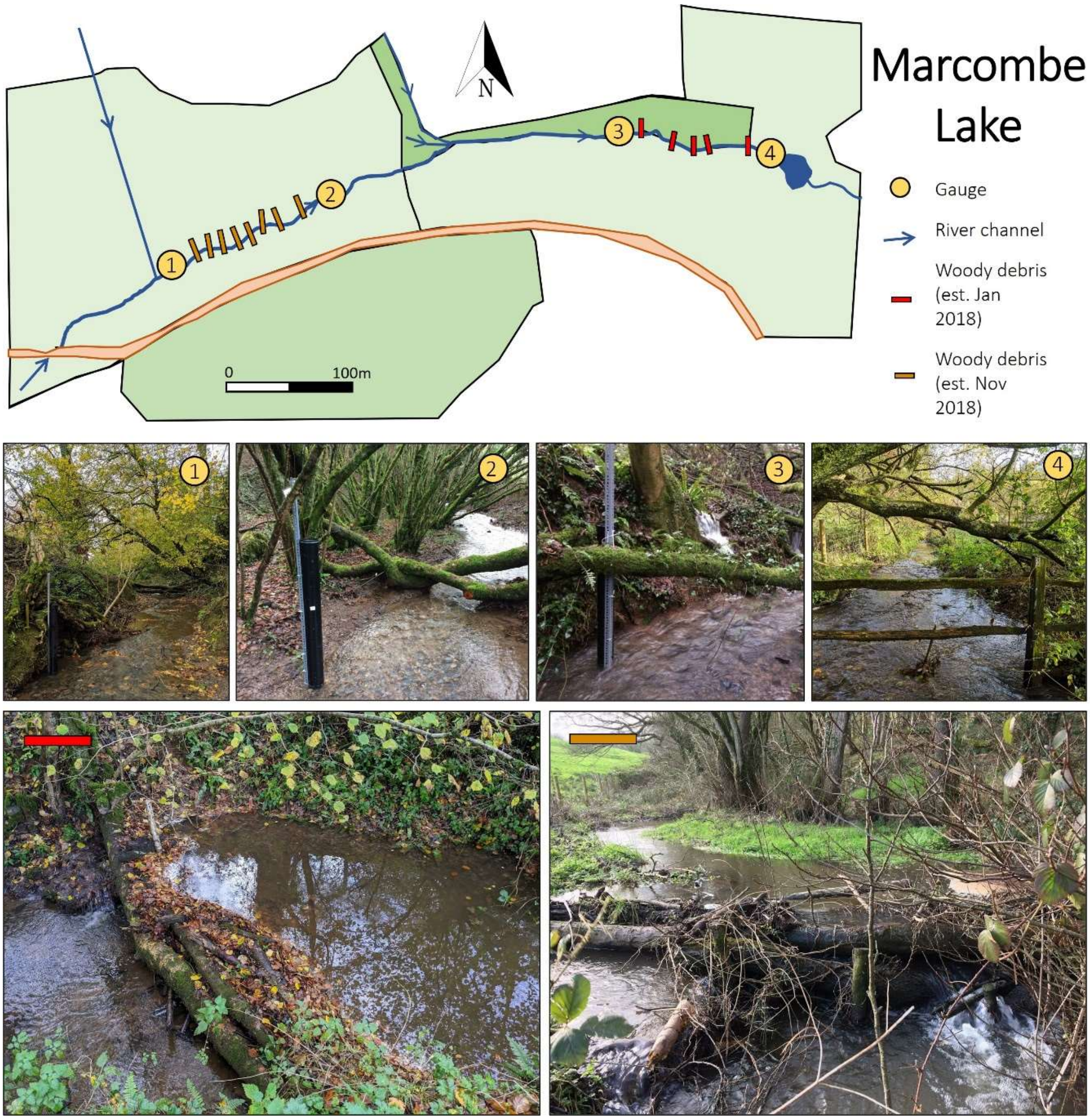

Figure 4.1. Schematic of leaky woody dam site, Tone catchment, Somerset (SW-England). Detailed are an upstream section and downstream section of leaky woody dams and their respective controls. Images correspond to their respective gauge (numbered 1 to 4) deployed immediately downstream of each section and a leaky woody dam example in the upstream (established in January 2018) and downstream section (established in November 2018). Schematic drawing and scale based on OS data (2021).

Flow was established using velocity-area methods (see Figure 4.2), as described in chapter 2.5.4, where fixed cross sections were established adjacent to each gauge. In total, 14 velocity-area measurements were made for each gauge (56 in total), covering low-medium flows. The flashy nature of this system and thus very short time periods over which the very highest flows (event peaks) occurred, meant that measuring ratings during the highest discharge periods proved very challenging. Therefore, rating extrapolations were conducted for stages >0.25m (0.233m^3/s) for gauge 1, >0.22m (0.17m^3/s) for gauge 2, >0.21m (0.28m^3/s) for gauge 3 and >0.27m (0.21m^3/s) for gauge 4. It is important to note that this does introduce additional uncertainties as the highest flow values cannot be verified against observed data and are reliant upon extrapolation of the rating curve. Using this data, system inflow and outflow for both study sections were established, enabling a comparison of the impact that leaky woody dams have locally.

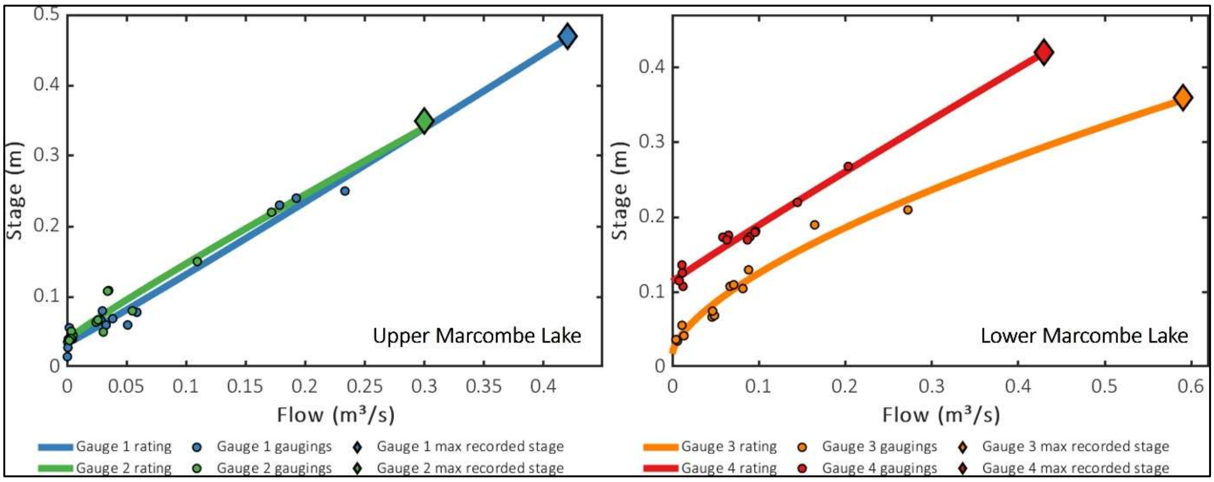

Figure 4.2. Gauge rating curves, converting stage data to flow for gauges 1-4. Detailed are recorded gaugings, maximum recorded stage and rating for each gauge.

4.3.2. Event definition

The event definition methodology outlined in chapter 3.5.6 was used to analyse the monitored data. This was used to systematically extract individual events from the flow dataset for all four in-channel gauges, based on a rules-based methodology, also applied in chapter 3. This enabled a thorough analysis of all events, ensuring that key event metrics (for example, flow peak time and height) are extracted in the same way between all events. The full workflow is presented in chapter 3.5.6. However, in summary, this involved using a minimum inter-event time of 3 hours, where rainfall and flow data were separated into individual events for analysis. The two study reaches were assessed separately, each with a control (gauge 1 or 3) or leaky woody dams (gauge 2 or 4) gauge. In addition, each separated event hydrograph was separated according to hydrograph percentiles: 5th, 25th,75th and 95th for the rising and recession limbs (see detail in chapter 3.5.6). Ensuring a consistent method to split event hydrographs was important to enable clear and consistent comparisons between gauges and events.

The largest flow events are of most interest in this study, as small events could already be assumed to produce minimal attenuation in-channel, for example as smaller flows are expected to travel unimpeded underneath the leaky woody dams. Therefore, for analysis in this chapter, the largest 30% magnitude events were separated. This event magnitude was determined as the total flow rise (5th-95th rising limb) of each event hydrograph. This was chosen over other possible metrics, as flow rise was deemed a clear indicator of overall system response. For example, the highest event peaks may not have had the highest system inputs if baseflows were already high prior to the event start (eg. high antecedent conditions). In addition, considering a metric such as event rainfall depth does not account for the impact of antecedent conditions and overland flow on overall system inputs. By ordering events according to their total flow rise, the highest 30% were subsequently extracted and the following metrics extracted for analysis.

4.3.3. Hydrological metrics

The analysis of hydrological metrics from the separated flow events was key to assess the impacts of leaky woody dams for flow attenuation by comparing key hydrological metrics for the control (1 and 3) and below leaky woody dam (2 and 4) gauges. Four hydrological metrics were extracted characterising how leaky woody dams impacted the flashiness, peak flow and attenuation of the event as follows:

Event API

For the produced time series, antecedent conditions were quantified by calculated the API value per day (eqn. 1), representing accumulated rainfall over time. API increases with additional rainfall (P) and declines where there is no new rainfall, according to a decay constant (k) of 0.9 (Heggen, 2001; Ali *et al.*, 2010).

$$API_d = kAPI_{d-1} + P_d \qquad \text{eqn. 1.}$$

Event API was determined as the extracted value on the day of the event start. This was used as a key control for further extracted metrics, in particular peak flow and the time from event end to system mass balance (see section 4.3.4). API was used on account of the expected critical role that antecedent conditions will play on pre-event flows and behind-dam and floodplain water storages. For example this was demonstrated for beaver dams by Puttock *et al*. (2017, 2021) and Graham *et al.* (2022), who highlighted how the attenuating impact of dams varied temporarily depending on pre-event, antecedent climatic conditions

Event rising limb slope

The rising limb slope angle was extracted to analyse how leaky woody dams changed the flashiness of the event. A smoother hydrograph rising limb is expected downstream due to the attenuation and storage of flows. To calculate this metric, the rising limb slope angle was extracted for each event, by extracting the slope (^{o}) between the 25^{th} and 75^{th} percentile values of the rising limb for each flow gauge. These percentile values were selected as the range to gain the core section of the rising limb.

Event peak attenuation

Peak flow values at all four gauges for each event were compared to examine the impact of leaky woody dams on peak flow attenuation. Event peak flow was extracted as the mean highest flow values from the extracted 95th-95th percentiles of each event. A comparison was made of the differences in event peak flow between gauges 1 and 2, and gauges 3 and 4 to consider both study sections separately. Extracting changes in event peak flow is a widely used hydrological metrics to assess the efficacy of leaky woody dams to attenuate flow (eg. Dixon *et al.*, 2016; Hankin *et al.*, 2017; Metcalfe *et al.*, 2017; Puttock *et al.*, 2021). A reduction in event peak flow downstream of leaky woody dams represents a slowing and storing of flow upstream. Indeed, flow that would have contributed directly to the event peak is released downstream more slowly, for example resulting in a lengthened recession limb.

A comparison between gauges 1 and 2, and gauges 3 and 4 were possible as outside of event periods and summed across longer time periods (eg. months), a mass balance is expected for flows for gauges 1 and 2 (Upper Marcombe Lake) and gauges 3 and 4 (Lower Marcombe Lake). This mass balance is due to no additional inputs in between the gauges, but with two separate inflows between gauges 2 and 3. Therefore, any difference in event peaks between gauges 1 and 2, and gauges 3 and 4 can be used to quantify peak flow attenuation. If peak values were the same, it would be expected that no flow attenuation had occurred behind the leaky woody dams, which is largely what is anticipated during very small flow events, where flows are expected to travel underneath the leaky woody dams unhindered. Conversely, if the leaky woody dams have slowed and stored flow temporarily, a higher peak upstream of the interventions (gauges 1 and 3) compared to downstream (gauges 2 and 4) would be expected.

Flow volume percentage change

A mass balance in flows within each study section (gauges 1 and 2 for Upper Marcombe Lake, and gauges 3 and 4 for Lower Marcombe Lake) is expected over time. Where flows are higher upstream of leaky woody dams (gauges 1 and 3) than downstream (gauges 2 and 4) during a rainfall event (short time scales), this is indicative of higher system inflows than outflows and indicates attenuation. Conversely, where flows are lower upstream of leaky woody dams than downstream during an event, this suggests more flow is leaving than entering the system, indicating system release. By examining the percentage differences in flow volume at gauges upstream and downstream of leaky woody dams, this inflow and outflow effect can be analysed in detail. The timing of total flow rate volume changes across each event is important to indicate not only the extent to which leaky woody dams may be impacting on downstream flows, but also when across an event system filling and spilling occurs. Flow volume percentage change was calculated based on the percentage difference between flow volume values (m^3) at gauge 1 compared to gauge 2, and gauge 3 compared to gauge 4 at a 1-minute timestep. Using this, percentage increases indicated system spilling or storage release, whilst percentages decreases indicated system attenuation.

4.3.4. Time from event end to system mass balance

As Marcombe Lake is a linear system, total flows over longer time periods (eg. outside of rainfall event periods) are expected to largely match up within Upper Marcombe Lake (gauges 1 and 2) and Lower Marcombe Lake (gauges 3 and 4). Whilst this can be simply verified by extracting total flow sums over monitoring time periods to ensure that mass balance is reached within these two study sections, it is also useful and ensures confidence in the extracted hydrological metrics to understand the time scales over which mass balance is reached after an event. As defined in detail in chapter 2.5.6. event separation occurs according to the most upstream gauge at each site (in the case of Marcombe Lake, gauge 1), where the event end is defined once there is a return to baseflow conditions (within a 10% threshold). However, it cannot be assumed that gauges 2, 3 and 4 also all reach pre-event baseflow conditions at the same time as the most upstream gauge, particularly with the hypothesis that flow is being attenuated upstream. Thus, it is important to understand the length of recession and importantly the time for system mass balance to occur.

The time from event end to system mass balance was extracted as the first occurrence where summed flows (from the event start) for the control and below leaky woody dam gauges matched, within 1% of each other. For each hour after the event end, flows for each gauge were summed and the time extracted where for Upper Marcombe Lake, gauges 1 and 2, and for Lower Marcombe Lake, gauges 3 and 4, mass balance was reached. It was anticipated that for some events mass balance would already be reached at the event end (<1% difference between gauges), in which case 0 hours would be assigned to this event. For other events, particularly those that are followed by multiple events, it was anticipated that the time to system mass balance would be much longer.

4.4. Results

4.4.1. Separated events and system mass balance

Firstly, for transparent analysis of both study sections, the monitored dataset for the full timeseries is presented for all four gauges and local rainfall (Figure 4.3). This dataset was used for event definition and metric extraction, with key characteristics detailed in Table 1. For Marcombe Lake, 8% of the total dataset is missing, principally due to site inaccessibility in spring-summer 2020 as a result of COVID. The leaky woody dams at Marcombe Lake have largely been left unmanaged since installation so that they function and evolve as naturally as possible (eg. any dam movement or the accumulation of silt and material has not been altered). Low flows for all gauges (<0.01m^3/s) were recorded during drier periods, where lower rainfall quantities were recorded during the summer months.

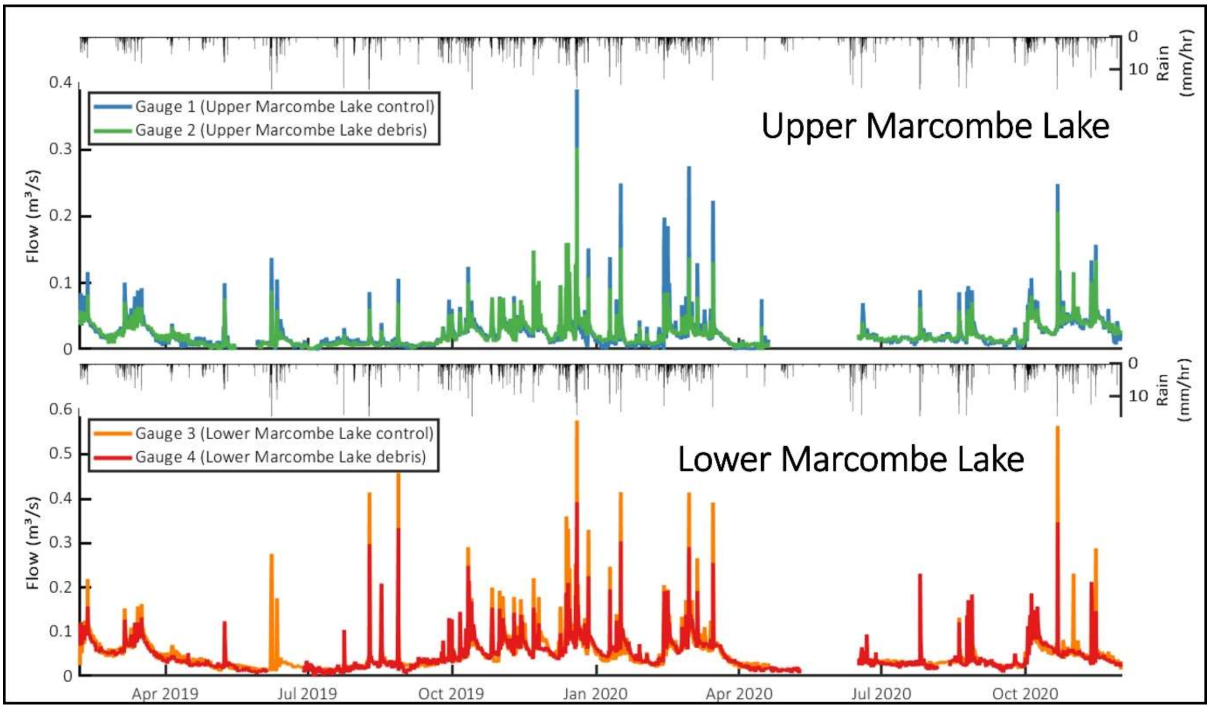

Figure 4.3. Monitored rainfall (top) and flow at each gauge (left) at Marcombe Lake, from January 2019 to December 2020. Gauges 1 and 3 are a 'control' (upstream of leaky woody dams) and gauges 2 and 4 are deployed immediately downstream of leaky woody dams.

For Marcombe Lake, whilst 190 events were defined, the highest 30%, based on 5^{th} – 95^{th} flow rise, were separated for analysis in line with the flow analysis methods applied in chapter 3.5.6. As small events could already be assumed to produce minimal attenuation in-channel, analysis focussed on the higher magnitude events, to allow for greater clarity when illustrating the impacts. For Upper Marcombe lake, extracting the highest 30% events, removed those with a flow rise <$0.014m^3/s$, based on gauge 2. For Lower Marcombe lake, this removed those with a flow rise <$0.019m^3/s$, based on gauge 4 (see Figure 4.4). Table 4.1 illustrates key metrics for the 48 analysed events, showing the ranges of event rainfall depth, total event duration (between event start and end), total rise and flow peak for each gauge. See the appendices for a full table of each of these metrics for each separated event.

	Upper Marcombe Lake		**Lower Marcombe Lake**	
	Gauge 1	**Gauge 2**	**Gauge 3**	**Gauge 4**
Total number of events extracted	190			
Mean event rainfall (mm)	17.4			
Max recorded rainfall (mm/hour)	87			
Max recorded in-channel flow (m^3/s)	0.42	0.3	0.59	0.41
Mean recorded in-channel flow (m^3/s)	0.021	0.02	0.057	0.053
Winter 2019/20 total summed flow (m^3)	178720	181920	500680	514670
Summer 2019 total summer flow (m^3)	75968	74375	217350	210930
Events analysed	57			
Range in event peak (m^3/s)	0.04 - 0.43	0.02 - 0.3	0.04 – 0.41	0.04 – 0.4
Total event rainfall depth range (mm)	9.4 – 87.2			
Range in event duration (hrs)	2 – 47.5			

Table 4.1. Key event characteristics for Upper and Lower Marcombe Lake. Mean and maximum values (rainfall and in-channel flow) are taken from all extracted events. Winter (December, January, and February) 2019/20 and summer (June, July, and August) 2019 total summed in-channel flow taken as two contrasting flow periods of 3 months.

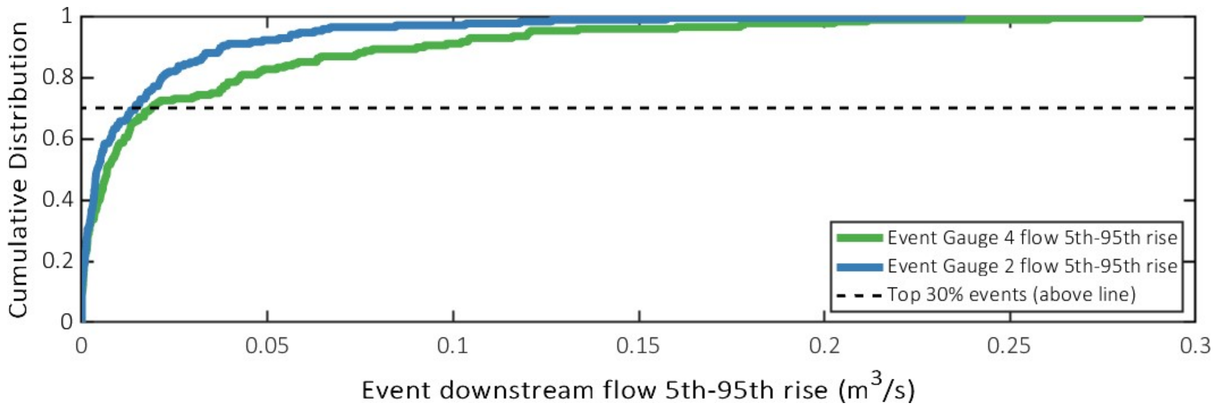

Figure 4.4. Cumulative distribution of events according to 5th-95th downstream rise, where the point of extraction of the top 30% magnitude events is indicated for Upper Marcombe Lake (gauge 2) and Lower Marcombe Lake (gauge 4).

4.4.2. What are the drivers of channel responses during rainfall events across the monitoring period?

This section will consider the seasonal distribution of events, including the rainfall depth, the captured event rise and peak, as well as the impact of antecedent conditions (API) and meteorological inputs (event rainfall) on driving these metrics. This will consider whether the largest 30% of events in terms of flow rise, also present the largest values in other metrics, such as event rainfall, flow peak and API. This is important to test the assumption that events with small flow rises will have minimal impacts for in-channel attenuation or downstream peak flow reduction justify why events have been selected according to flow rise.

Firstly, the seasonal distribution of events, including their size (event rainfall depth) and their implications for event flow rise and peak were considered (Figure 4.5). Events with high event rainfall depths occur throughout the year, although it is only during the winter period where events with higher flow rises and thus event peaks occur (Figure 4.5). As events with high flow rises are hypothesised to be required for any impacts of leaky woody dams to be seen, this suggests that the impacts of these features may only be apparent during the winter period at this study site.

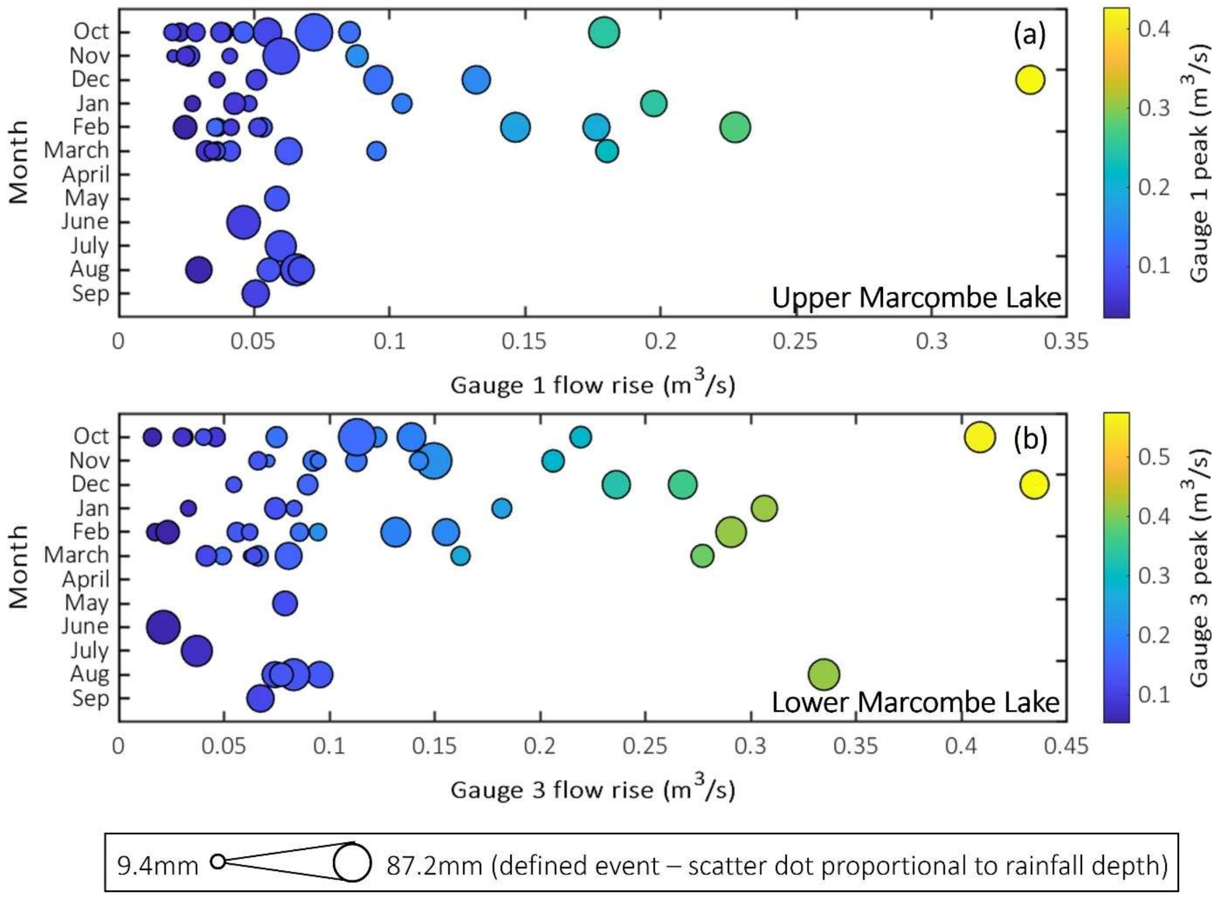

Figure 4.5. Impact of seasonality (month) and rainfall event rainfall depth on event magnitude. This shows a comparison with control gauge flow rise for Upper and Lower Marcombe Lake. Each scatter dot represents 1 analysed event (top 30% flow rise).

Secondly, the impact of key system inputs: event rainfall depth (mm) and antecedent conditions (API value) on the control gauge peak flow is analysed to understand the extent to which increasing sizes of peak flows can be accounted for by either direct metrological inputs (event rainfall) or existing system storage (antecedent conditions). Plotting the relationships between API (Figure 4.6a) and event rainfall depth (Figure 4.6b) and system inflow event peak flow (gauge 4) demonstrates that both present very similar correlations with peak event flows (correlation coefficient of 0.38 for rainfall, compared to 0.39 for API).

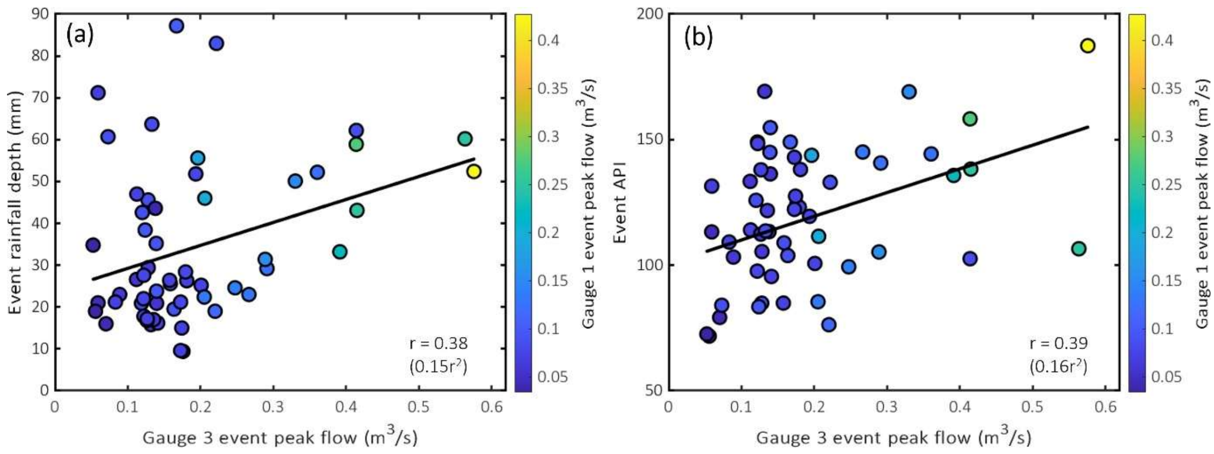

Figure 4.6. Impact of hydrological inputs (event rainfall depth, mm (a) and event API value (b) on system outflow (gauge 4). Event peak inflow (gauge 1) is indicated by the colourbar.

4.4.3. What is the impact of leaky woody dams on channel flows, based on total in-channel attenuation and temporary storage?

To assess the response of leaky woody dams to rainfall events and their efficacy to attenuate flow, the impact of flows upstream and downstream of leaky woody dams are assessed by analysing key aspects of event hydrographs. Firstly, the effects for the rising limb slope are considered (Figure 4.7) to evaluate the impact of leaky woody dams on event inflow. Next, a comparison is made of event peak heights upstream and downstream of leaky woody dams (Figure 4.8) to evaluate peak flow attenuation. In line with this, the change in flow downstream of leaky woody dams is illustrated in detail for the highest-magnitude event for the Upper and Lower Marcombe Lake study sections (Figure 4.9).

Collectively for these metrics, reductions in values in gauges downstream of leaky woody dams (gauges 2 and 4 for Upper and Lower Marcombe Lake, respectively), are indicative of attenuation (higher system inflow than outflow). In the same way, reductions in values in gauges upstream of leaky woody dams (gauges 1 and 3 for Upper and Lower Marcombe Lake, respectively), are indicative of storage (eg. in-channel) release and higher outflow than inflow. To achieve system mass balance (even if over a longer term than within the extracted event hydrograph), any higher system inflows (attenuation) or higher system outflows (storage release) are expected to largely balance out within each study section. To highlight and examine this system flow release, the time taken to achieve system mass balance (equal summed flows upstream and downstream of leaky woody dams) is illustrated (Figure 4.10).

Event rising limb slope

Across the events, differences in hydrograph rising limb slope angle are compared between gauges upstream and downstream of leaky woody dams (Figure 4.7). This demonstrated that downstream of leaky woody dams, rising slope angles were reduced by up to 9.2° for Upper Marcombe Lake and up to 10.4° for Lower Marcombe Lake. This overall reduction is associated with high variability depending on the event, with small increases in slope angle downstream of leaky woody dam also extracted (7 out of 57 events for Upper Marcombe Lake and 14 out of 57 events for Upper Marcombe Lake). Notably from Figure 4.7, events with the highest slope angle reductions typically also show the highest event peak flow.

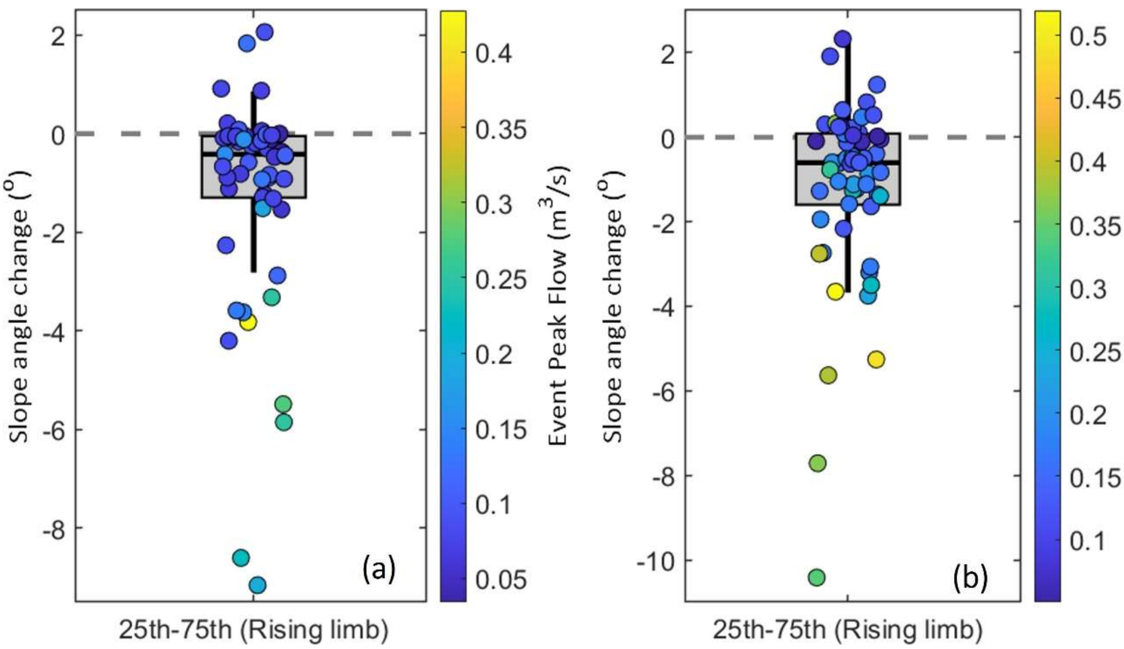

Figure 4.7. Impact of leaky woody dams on event hydrograph rising limb (25th-75th percentiles), based on change in angle from a gauge upstream of debris to a gauge immediately downstream. Results are shown for Upper (a) and Lower Marcombe Lake (b).

Event peak attenuation

Next, the impact of leaky woody dams on event peak flows are examined by comparing peak flow heights upstream (gauges 1 and 3) and downstream (gauges 2 and 4) of leaky woody dams, illustrated by Figure 4.8, where all values and percentage change between each study section are shown by Table 4.2. Figure 4.8 illustrates firstly a 1:1 ratio line on both plots to represent the expected correlation between gauge peaks if there were no leaky woody dams, due to there being no additional flow inputs or channel interventions, and a relatively small distance (120m) between gauges. Peak flow reductions downstream of leaky woody dams are found for certain events, notably for those with the highest rainfall event depths. Of these events, the maximum peak flow difference is greater for Lower Marcombe Lake, compared to Upper Marcombe Lake, with a reduction of 0.22m^3/s (38% reduction), compared to 0.14m^3/s (49% reduction) respectively. For smaller magnitude events, gauge peak flow differences are less pronounced and largely follow the 1:1 line, with some variation, equating up to 0.06m^3/s flow additions downstream of leaky woody dams (60% change) for Upper Marcombe Lake and up to 0.16m^3/s flow additions downstream of leaky woody dams (217% change) for Lower Marcombe Lake. With increase in peak flow, there is greater divergence from the 1:1 line, indicating a greater peak flow difference downstream of leaky woody dams. This is particularly evident for events with the highest rainfall.

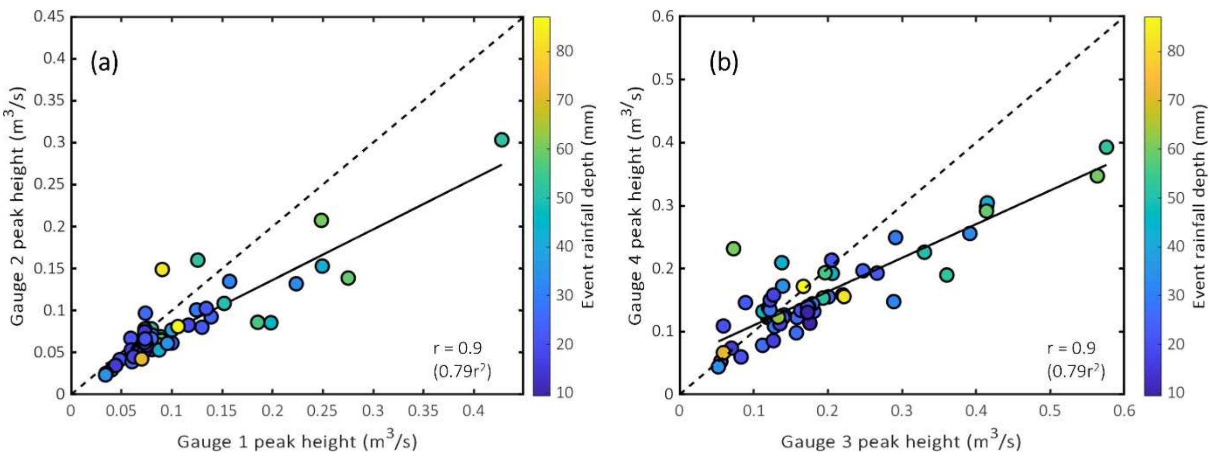

Figure 4.8. Comparison of event peak flow for the Upper Marcombe Lake (a) and Lower Marcombe Lake (b) study sections.). Colourbar indicates corresponding event rainfall depth.

Event	Event depth (mm)	Gauge 1 peak (m^3/s)	Gauge 2 peak (m^3/s)	Upper Marcombe Lake peak % change	Gauge 3 peak (m^3/s)	Gauge 4 peak (m^3/s)	Lower Marcombe Lake peak % change
05/02/19	20.9	0.08	0.06	-30.37	0.12	0.12	3.03
09/02/19	19	0.12	0.08	-29.04	0.22	0.16	-28.11
05/03/19	45.6	0.10	0.07	-28.06	0.15	0.13	-16.27
12/03/19	22	0.08	0.06	-23.86	0.12	0.12	0.09
14/03/19	25.6	0.09	0.07	-26.94	0.16	0.12	-22.78
16/03/19	19.5	0.09	0.06	-30.95	0.16	0.13	-18.30
08/05/19	38.4	0.10	0.08	-23.18	0.12	0.13	0.92
08/08/19	62.2	0.09	0.06	-28.50	0.41	0.30	-27.98
16/08/19	43.6	0.04	0.03	-26.88	0.14	0.21	51.84
28/09/19	47	0.08	0.05	-28.98	0.11	0.13	17.35
05/10/19	23	0.06	0.06	-11.54	0.09	0.15	64.16
09/10/19	21	0.05	0.04	-14.27	0.06	0.11	84.16
10/10/19	29.2	0.12	0.10	-19.15	0.29	0.25	-14.46
26/10/19	25.2	0.08	0.08	3.74	0.20	0.16	-22.70
30/10/19	51.8	0.08	0.08	-2.06	0.19	0.15	-20.82
01/11/19	9.4	0.07	0.06	-9.69	0.18	0.11	-35.56
02/11/19	26.3	0.07	0.08	6.50	0.18	0.13	-27.01
09/11/19	28.4	0.08	0.07	-12.13	0.18	0.14	-19.72
13/11/19	15	0.07	0.07	2.15	0.17	0.14	-20.03
14/11/19	20.9	0.06	0.07	12.79	0.14	0.12	-10.85
21/11/19	83	0.09	0.15	64.35	0.22	0.16	-29.87
08/12/19	26.4	0.07	0.10	31.19	0.16	0.10	-37.81
12/12/19	52.2	0.13	0.16	27.16	0.36	0.19	-47.37
19/12/19	52.4	0.43	0.30	-29.09	0.58	0.39	-31.81
24/12/19	15.8	0.06	0.05	-11.28	0.13	0.12	-8.87
26/12/19	50.1	0.15	0.11	-28.63	0.33	0.23	-31.59
09/01/20	24.6	0.14	0.09	-33.53	0.25	0.20	-20.55
13/01/20	16.2	0.08	0.05	-29.13	0.14	0.13	-10.52
14/01/20	29.4	0.07	0.05	-21.02	0.13	0.11	-15.69
16/01/20	43.1	0.25	0.15	-38.72	0.42	0.30	-26.70
28/01/20	16	0.04	0.03	-21.62	0.07	0.07	5.17
02/02/20	19	0.03	0.03	-27.71	0.06	0.05	-5.40
09/02/20	34.8	0.03	0.02	-31.69	0.05	0.04	-15.95
12/02/20	46	0.20	0.09	-56.91	0.21	0.19	-6.64
14/02/20	55.6	0.19	0.09	-53.62	0.20	0.19	-1.47

16/02/20	23.8	0.10	0.06	-38.78	0.14	0.12	-12.67
24/02/20	17	0.07	0.05	-25.56	0.14	0.11	-17.11
27/02/20	21.2	0.08	0.05	-33.39	0.17	0.14	-19.28
28/02/20	58.9	0.28	0.14	-49.59	0.41	0.29	-29.66
01/03/20	9.6	0.07	0.05	-29.69	0.17	0.13	-24.44
05/02/20	23	0.13	0.08	-38.34	0.27	0.19	-27.67
09/03/20	26.6	0.06	0.04	-35.46	0.11	0.08	-30.15
13/03/20	16.8	0.06	0.05	-27.51	0.13	0.09	-32.43
15/02/20	33.2	0.22	0.13	-41.01	0.39	0.26	-34.71
18/06/20	71.2	0.07	0.04	-39.48	0.06	0.07	12.50
25/07/20	60.7	0.09	0.06	-28.32	0.07	0.23	217.61
19/08/20	63.7	0.09	0.06	-31.22	0.13	0.12	-7.64
24/08/20	42.6	0.09	0.05	-39.29	0.12	0.14	15.12
24/08/20	35.2	0.10	0.06	-36.29	0.14	0.17	23.82
02/10/20	87.2	0.11	0.08	-23.70	0.17	0.17	2.82
04/10/20	27.6	0.11	0.08	-24.15	0.18	0.19	7.19
06/10/20	17.8	0.08	0.06	-22.00	0.12	0.15	22.84
07/10/20	17.2	0.07	0.06	-15.72	0.13	0.16	24.62
21/10/20	60.2	0.25	0.21	-16.57	0.56	0.35	-38.41
24/10/20	21.2	0.07	0.07	-10.03	0.08	0.06	-28.11
11/11/20	22.4	0.13	0.10	-23.62	0.21	0.21	4.02
14/11/20	31.4	0.16	0.13	-14.47	0.29	0.15	-48.93

Table 4.2. Comparison of event peak flows for gauges 1-4 across both study sections and the resultant peak flow % change between gauges upstream and downstream of leaky woody dams. Metrics extracted from all analysed events (within highest 30% magnitude). Event date refers to the date at the event start and event depth states the total event rainfall.

Flow volume percentage change

The highest peak event: 19th of December 2019 is presented Figure 4.9, to illustrate in detail the processes of peak flow attenuation detailed. High flow responses are shown, with a 5th-95th channel rise of 0.39m^3/s (gauge 3) and marked flow volume differences between gauges upstream and downstream of leaky woody dams. For Upper Marcombe lake, flow volume percentage reduction is greatest at the peak, with a 40% reduction. For Lower Marcombe lake the highest flow volume percentage reduction is just before the peak, with a 27.2% reduction. For Lower Marcombe Lake, downstream flow reduction switches to flow addition by the 75th percentile of the recession limb. For Upper Marcombe Lake, this switch is 3.5 hours later in the recession limb, in the 25th percentile.

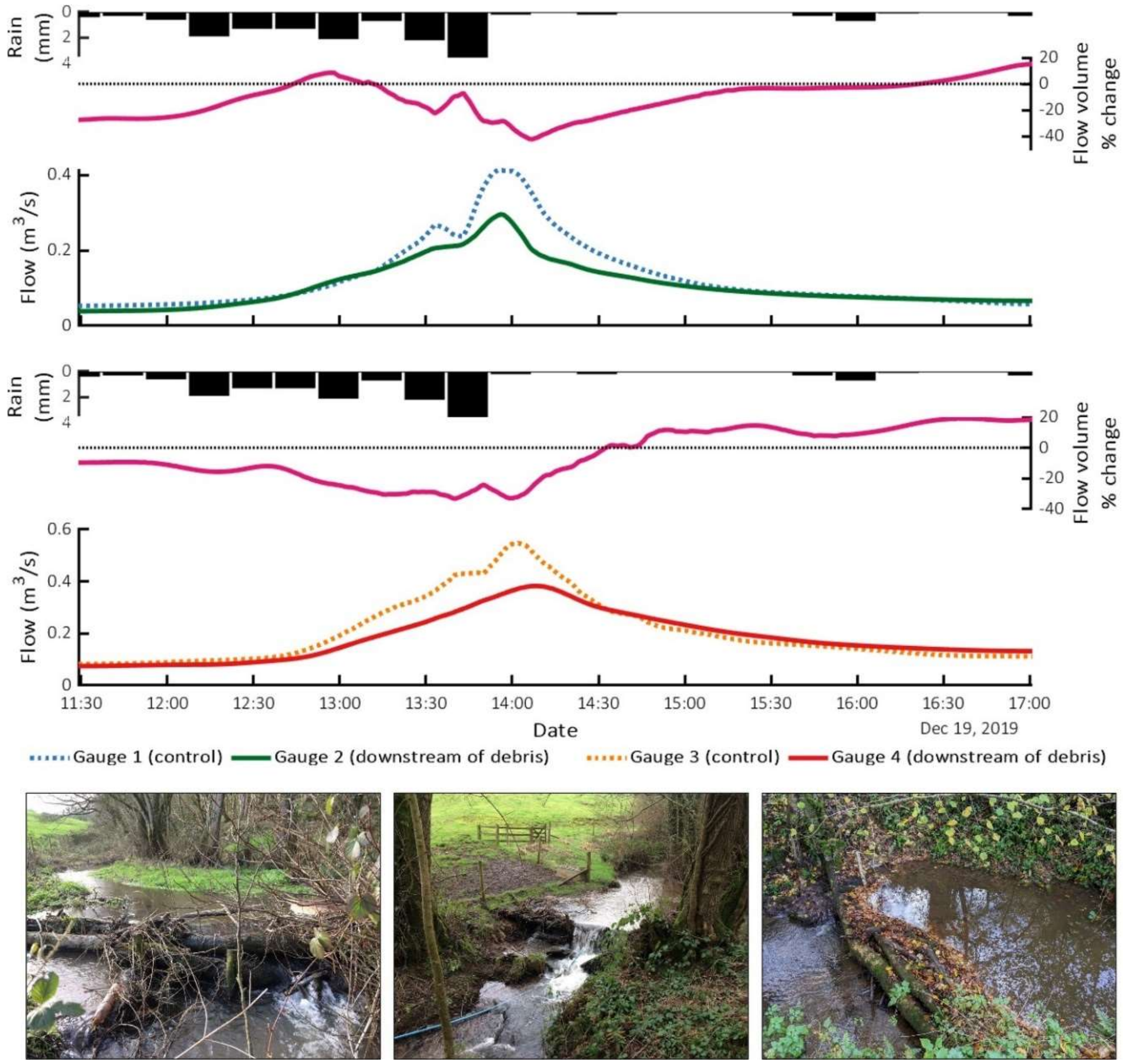

Figure 4.9. 19th December 2019 event detailing flow for Upper Marcombe Lake (gauges 1 and 3) and Lower Marcombe Lake (gauges 2 and 4). Flow volume % change represents the impact of leaky woody dams on downstream gauges. Images show ponding of water behind the dams and water release during higher baseflow periods in the 2019/20 winter period.

Time from event end to system mass balance

From visual time series analysis and in the event presented by Figure 4.9, it is clear that within the time frame of the separated events, system outflow (gauges 2 and 4, respectively) does not always equal system inflow (gauges 1 and 3, respectively). It is important to examine timing of water storage and the overall system mass balance to ensure the quality of the data being analysed (i.e. differences in peak flows are not solely due to uncertainties in the rating curves). Over the whole monitoring period, total summed flows for gauge 1 and gauge 2 and gauge 3 and gauge 4 reach a mass balance, for example within 3% of each other for two example (summer and winter) periods presented in Table 4.1. Key to the function and expected impact of leaky woody dams is that across events, temporary attenuation is anticipated behind leaky woody dams, as in-channel storage and where flow has been pushed onto the floodplain. This is expected to result in greater inflow than outflow whilst leaky woody dams are holding back flow. As the system inputs (eg. event rainfall) subside (assumingly in the latter stages of the event), it is expected that system outflows will be higher than system inflows. Therefore, during events, and likely for a period after rainfall, a system mass balance is not expected if leaky woody dams are successfully attenuating flow. This can also be reflected as anticipated elevated baseflows downstream of leaky woody dams during lower flow periods (eg. following event times) as flow spilling (greater outflow than inflow) is still occurring.

Figure 4.10. illustrates the time taken for system inflows and outflows to match (mass balance) after the event end for all analysed events, for Upper and Lower Marcombe Lake. This is plotted against event API, which was selected as a key control on flow recession following events, based on its deemed critical role on controlling flows for beaver dams studied elsewhere (eg. see (Puttock *et al.*, 2017, 2021; Graham *et al.*, 2022). This illustrates that the time taken from the event end for system inflows and outflows to match varies hugely, where for some events, mass balance is reached by the end of the event (0 hours), whilst for others, the time can be up to 980 hours (40 days). Of the extracted events, only 5 present system mass balance within 1 hour of the defined event end. This increases to 8 events within 5 hours of the defined event end. This reflects that marked elevated baseflow following event periods can occur, where gauges upstream of leaky woody dams present

lower flows than gauges downstream of leaky woody dams for potentially long periods after the event end.

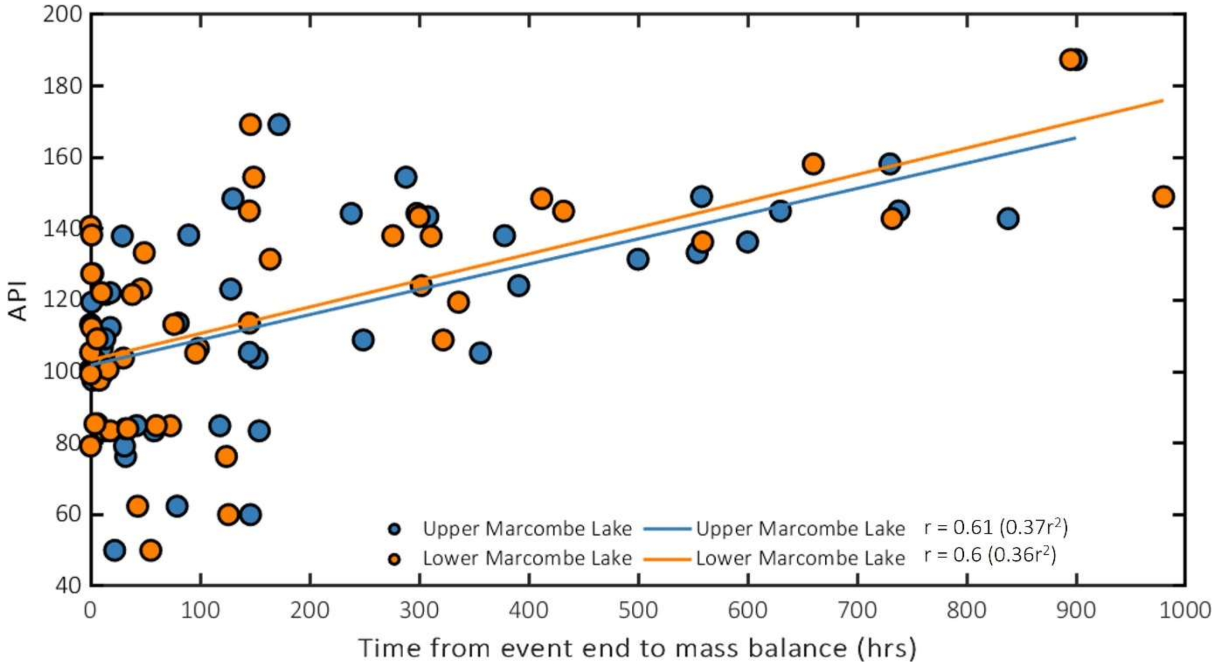

Figure 4.10. Time taken for system inflows and outflows to reach mass balance after the event end, in relation to event API. For Upper Marcombe Lake, this is the time for gauges 1 and 2 to match and for Lower Marcombe Lake, this is for gauges 3 and 4 to match. Time is extracted by hour and the first occurrence of where inflows and outflows match within 1%. Summed flows are defined from the event start to the defined hour after the event end.

A potentially key control on the time from event end to mass balance was found to be event API, which was plotted against time from event end on Figure 4.10. This is key to highlight the extent to which antecedent conditions may control the time for system flows to balance out. A positive correlation was reported, with a r value of 0.61 for Upper Marcombe Lake and 0.6 for Lower Marcombe Lake, based on Pearson's corelation coefficient. This correlation is perhaps particularly notable for events with the highest API values, which also represent among the longest times from event end to system mass balance. For instance, no events with API values lower than 100 have a time from event end to mass balance longer than 154 hours. It is important to note that high variation (r-squared values of 0.37 and 0.36) is also evident, which is particularly marked for events that present small times from event end to mass balance. Indeed, for events where mass balance occurs within 1 hour of the event end, API values range between 79 and 140.

The production of elevated baseflows downstream of leaky woody dams following events is illustrated further by Figure 4.11 which presents an extenstion of the 19th December 2019 event presented by Figure 4.9. At the defined event end (according to the event separation workflow) summed system inflow (gauge 1) is 15.5% higher than system outflow (gauge 2) for Upper Marcombe Lake, where system mass balance (within 1%) is extracted 10.5 hours after the defined event end. For Lower Marcombe Lake, summed system inflow (gauge 3) is 9% higher than system outflow (gauge 4), where system mass balance (within 1%) is extracted 6.5 hours after the defined event end. This shows temporary elevated baseflows downstream of leaky woody dams (gauges 2 and 4) following the event end. It is important to note that for other events, these elevated baseflows extend for markedly longer time periods.

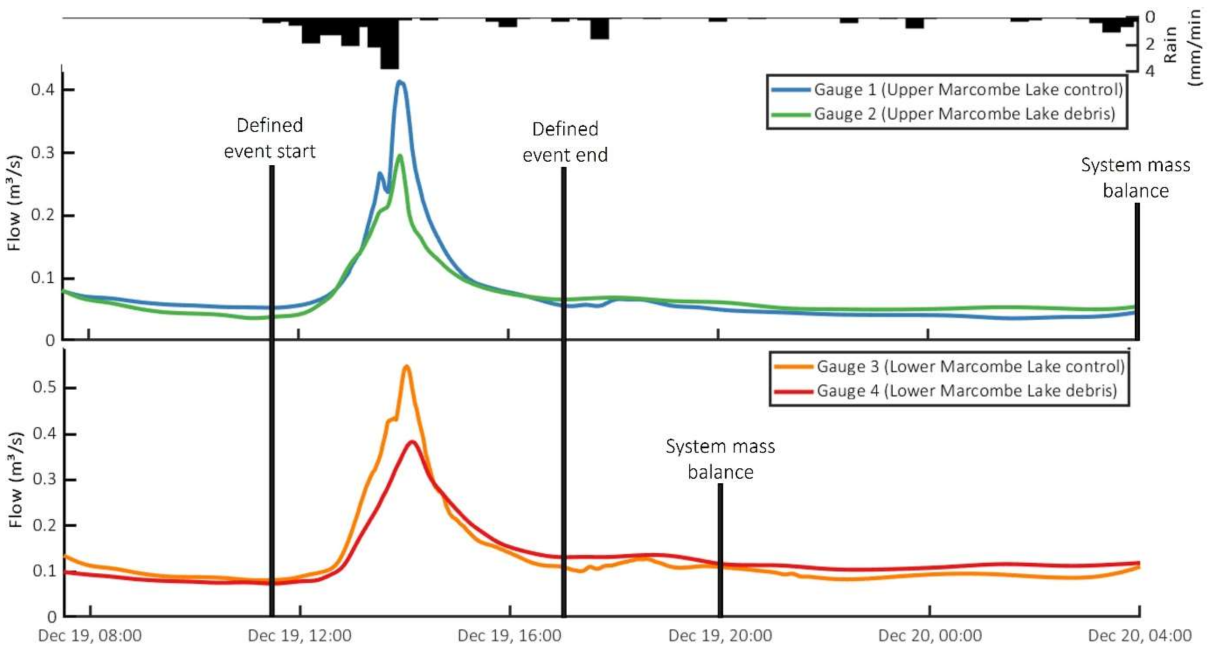

Figure 4.11. Extended version of 19th December 2019 event (Figure 4.9) showing the extracted event, according to event separation workflow, from defined event start to end. The hours afterwards illustrate the increased baseflow occurring following the deemed event end, where the point of system mass balance (within 1%) from the event start is indicated.

4.5. Discussion

4.5.1. Flow attenuation across rainfall events

The analysis of rainfall events between January 2019 and December 2020 revealed the potential for leaky woody dams to generate peak flow and flashiness reductions downstream of interventions. We find marked peak flow reductions downstream of leaky woody dams, particularly for the events with the highest rainfall depths and those with the largest actual peaks, which showed peak flow reductions of up to 56% (Upper Marcombe Lake) and mean peak flow reductions of 21% and 7% for Upper and Lower Marcombe Lake, respectively. This is reflected in the reductions in rising limb slope angles extracted downstream of leaky woody dams, relative to upstream, which is also most notable for the largest peak events.

These results compliment the overall impacts presented in empirical datasets elsewhere. A study by Wenzel et al. (2014) demonstrated small decreases in peak flow, alongside temporary channel storage where leaky woody dams were deployed, during artificial 60-minute long high-magnitude flow events, where an upstream flap gate weir was opened for 10 minutes at the start of each experiment. A hydrograph shape change was presented, with a shift in flow volume across events, where 22% of total flow volume was shifted from the event peak to periods of lower flow values across the 60-minute test. This pattern is seen in this study where downstream of leaky woody dams (gauges 2 and 4) there is a reduction in rising limb slope angle, relative to the upstream control (gauges 1 and 3), generating peak flow reductions. In addition, Norbury *et al.*, (2021) illustrated overall peak flow reductions downstream of leaky woody dams (mean of 27.3%), which as with the results in this chapter showed greater reductions in higher precipitation events. Norbury *et al.*, (2021) presents a particularly notable catchment comparison study due to the crossovers in monitoring periods, where in a NW England catchment, monitoring was conducted between August 2019 – October 2020, compared to January 2019 – December 2020 in this chapter.

The release of flow is markedly slow for most events recorded in this chapter, and indeed for these largest magnitude events that have been highlighted, system mass balance does not occur for weeks after the end of the event. This was typical for winter events and particularly those with high API values, where events were quickly followed by further events within 24 hours, if not by sporadic and sparse rainfall (eg. not constrained within the event definition methodology) within hours. Therefore, unless there is a sustained period of no rainfall, flow additions to the system are occurring whilst the system is still spilling and thus a mass balance is not achieved as system storage (even if small) is maintained. In contrast, where events are followed by sustained periods of no rainfall, with low antecedent conditions, system flows are allowed to return to their lowest values, with minimal system storage.

A slow release of flow following events may be accounted for by the leaky nature of dams, blocking full flow release, floodplain storage as a result of horizontal water flows during events, and the production of elevated baseflows downstream of dams, which are maintained even during longer, drier periods, which are effects reported for beaver dams (Majerova *et al.*, 2015; Puttock *et al.*, 2017; Brazier *et al.*, 2021). Indeed, although a lesser reported impact of leaky woody dams, their benefits for elevating baseflows downstream of interventions has been identified by Norbury *et al.*, (2021), who illustrated that for low flow periods ($<0.1m^3/s$), gauged flow downstream of leaky woody dams was increased by 27.1% following leaky woody dam installation. Small increases in baseflows downstream of leaky woody dams is reflected in this chapter by the typical long time periods following event ends before summed flow values equal each other at gauges deployed upstream and downstream of leaky woody dam stretches. Although in this chapter and by Norbury *et al.*, (2021), these represent relatively small values in total (eg. $<0.01m^3/s$ changes), even marginal baseflow increases as a result of NFM implementation could suggest their potential impacts for wider landscape wetting, increasing wider landscape resiliency, which has been reported elsewhere for beaver dams (eg. see Larsen, Larsen and Lane, 2021; Pearce *et al.*, 2021). Water storage as a result of the presence of dams is expected to vary over a range of time scales, including between events and seasonally, which may highlight the impact of longer-term water retention within the landscape, driven by the produced channel complexities, such as dam ponds and new floodplain reconnections (Dixon *et al.*, 2016; Brazier *et al.*, 2021).

It is important to note that a wide range of peak flow changes from upstream to downstream of leaky woody dams were extracted across the analysed events. This is especially apparent for smaller flow events, where both increases and decreases in peak flow downstream of leaky woody dams were extracted. This was particularly notable for Lower Marcombe Lake, where 10 out of 48 events showed increases ($0.001 - 0.16m^3/s$) in peak flow downstream of leaky woody dams. This may be due to events occurring in quick succession to previous, larger events, where attenuated flow within the system is still spilling or may be due to undetected additional system inflows downstream of leaky woody dams but that are captured by gauges 2 or 4. This level of variability was seen in results in empirical studies elsewhere, which have also documented both increases and decreases in peak flow downstream of leaky woody dams (despite an overall marked flow attenuation).

Following the deployment of leaky woody dams, event analysis by Norbury *et al.*, (2021) reported percentage differences in peak flow between -11.4% and 124.8%, upstream and downstream of interventions. This level of variation is comparable to peak flow percentages changes downstream of leaky woody dams seen in this chapter which vary between -53% and 31% for Upper Marcombe Lake and -49% and 217% for Lower Marcombe Lake. Higher percentage flow peaks (27%) downstream of leaky woody dams during Storm Ciara (8-10th February, 2020) in Norbury *et al.*, (2021), were attributed to additional inflows which occurred upstream of gauging deployed downstream of all leaky woody dams. This contrasted to flow reductions of 4.3% downstream of leaky woody dams during subsequent Storm Dennis (15-16th February 2020). The differences in channel responses between these two large events in Norbury *et al.*, were attributed to longer duration, lower intensity rainfall during storm Dennis. Storms Ciara and Dennis contributed to recorded breaking rainfall totals and recorded flows across the UK (Parry *et al.*, 2020), with the effects also experienced in the South-West of England at Marcombe Lake during the monitoring period of this chapter. Storm Ciara (extracted 9th February 2020 event) resulted in percentage peak flow reductions of 31% for Upper Marcombe Lake and 16% for Lower Marcombe Lake. Storm Dennis (extracted 15th February 2020 event) resulted in percentage peak flow reductions of 53% for Upper Marcombe Lake and 1.5% for Lower Marcombe Lake.

Marked variation in peak flow changes upstream and downstream of deployed leaky woody dams have been reported elsewhere. Dixon *et al.* (2016) who despite showing an overall trend of peak flow reduction with increased channel restoration, demonstrated highly variable results, with both peak flow increases and decreases under leaky woody dam scenarios. Such variability was largely avoided in Wenzel et al., (2014) as artificial flow events were generated through controlled water release upstream, meaning each run had controlled conditions, for instance including the same quantity of water passing through the system. Modelled results by Thomas and Nisbet (2012) reported no marked changes to event flow peaks, despite a reduction in velocity and overall delay in peak travel time downstream by on average 2-3 minutes. This was attributed to storage occurring until flow reached the dam height, resulting in peak flow values being largely unaffected by the leaky woody dams. Elsewhere, whilst results showing reductions in average stage height following NFM implementation were reported by Short *et al.* (2019), this study reported on a range of NFM structures collectively (leaky woody dams alongside gully stuffing, earth bunds, grips and culverts) and thus differentiating between each group of structures, to quantify the impact of leaky woody dams is difficult. This highlights the significance of studies that have examined the impact of singular types of NFM features so that their individual contribution (within wider configurations) can be determined. Considering variations in impacts in this chapter and elsewhere may highlight the importance of critical assessment for leaky woody dam deployment if they have the potential to increase as well as decrease downstream peaks. However, it is important to note that flow additions may also be as a result of external factors, such as previously undetected system inflows (eg. Norbury *et al.*, 2021)

The impact of leaky woody dams on downstream flows differs between Upper and Lower Marcombe Lake, in terms of changes to the rising limb and peak flow. This may be due to differing characteristics between the two study sections, firstly in terms of the quantity of dams (8 in Upper Marcombe Lake, compared to 5 in Lower Marcombe Lake) which may allow varying quantities of storage. In addition, the floodplain topography in Lower Marcombe Lake is lower and considerably less incised. This is likely to encourage greater floodplain reconnection and diversion of flow onto the floodplain, as channel stage is more likely to reach the height of the floodplain. In contrast, where the channel is highly incised, and the floodplain is high, the topography does not naturally lend itself to floodplain reconnection. Through modelling approaches, leaky woody dams in downstream catchment channel reaches have shown greater efficacy for attenuation and flood risk reduction (eg. Metcalfe et al., 2017). However, this is an area of high uncertainty in current empirical studies that have studied artificially deployed leaky woody dams.

4.5.2. Comparison with beaver dams

Although these storage dynamics are not directly measured in this study for these leaky woody dams, elsewhere in the literature, the dynamics of temporary storage from in-channel woody dams is reflected from beaver dams following species re-introductions in Cornwall and Devon, (reported in Puttock *et al.*, 2017, 2021). Following reintroductions in 2011, total estimated water storage volumes increased to a storage capacity of 1000m^3 by 2015, on account of the increasing number of beaver pond structures, that reached 13 by 2016. Detailed and regular topographic surveys were required to quantify the dynamics of these storage volumes. In contrast, the monitored offline ponds in chapter 3 are highly static and whilst future maintenance may require pond de-silting, the overall pond volume capacity of both ponds is expected to remain largely unchanged. This makes the impacts of in-channel storage easier to predict and quantify than that of leaky woody dams, with easier verification for future flood risk assessments.

Leaky woody dams share many similarities with dams constructed by beavers (Muhawenimana *et al.*, 2021). Based on data presented here and that in the literature, both have the ability to attenuate flow as a result of the generation of dam pools and the re-direction of flow onto the floodplain, enhanced through floodplain reconnection (Sear *et al.*, 2010; Hankin *et al.*, 2020; Puttock *et al.*, 2021). However, in comparison to leaky woody dams, beaver dams have a far more pronounced effect on the landscape. Firstly, beaver dams are highly dynamic, rarely as 'leaky' as they are regularly maintained to ensure flow is blocked and are typically associated with larger scale river system and wetland modification as a product of their habitat creation (Puttock *et al.*, 2017). Whilst leaky woody dams by design span 1m across unrestored rivers, networks of beaver dams can dominant a river system landscape. For example, beaver dams constructed following species reintroductions in Devon (UK) in 2011, spanned up to 30m, creating pond area of >1800m^2 (Puttock *et al.*, 2017). In contrast, the leaky woody dams studied here are situated in a small, wooded valley channel, where a small area of farmland was dedicated to NFM. Reported by Puttock *et al.*, (2017), beaver dams were found to produce average percentage reductions in peak event flow of 35% (up to 66%) downstream of beavers, demonstrating overall significant attenuating impacts on system flow. The variability of the results produced in these study reaches perhaps highlights the advantages of species that inherently alter a river systems morphology for slowing flow, rather than relying on human-based introduction of wood.

4.5.3. Limitations and uncertainties

Finally, key limitations and uncertainties of this study and their implications for the results are outlined. From the datasets and events in this chapter, analysis has highlighted the potential for peak flow reductions downstream of leaky woody dams, particularly in high flow events over a 23-month period. A longer dataset would enable a more detailed examination of the causes or sources of the variation associated with these results, along with the reported peak flow reductions (Norbury *et al.*, 2021). This would also enable consideration of the changing impact of these newly deployed leaky woody dams as they evolve, where based on the literature, the continued accumulation of debris and sediment would expect to cause increased attenuation. Differing leaky woody dam designs by Muhawenimana *et al.*, (2021) showed that non-porous barriers resulted in twice the quantity of flooded area.

We also need to consider the likelihood of rating curve uncertainty at Marcombe Lake, which may have resulted in over/under estimation of flow and storage. At both study reaches, total flow storage (attributed to the presence of leaky woody dams) was calculated based on the difference between an upstream and a downstream gauge. Using the largest recorded event as an example (19th December 2019, see figure 4.9), total flow storage was calculated to be 437m^3 for Upper Marcombe Lake and 452m^3 for Lower Marcombe Lake, based on the difference in total summed flow between gauge 1 and 2, and gauges 3 and 4, respectively, from the event start to the event end.

For Upper Marcombe Lake, there is a 120m channel section between gauges 1 and 2, where the river channel is approximately 2.5m wide (at both deployed gauges). Therefore, for 437m^3 of storage to occur during the largest recorded event, within this study section, this would assume there was on average a water depth of 1.45m. Given that the highest stage recorded at Upper Marcombe Lake was <0.5m, it is not feasible for this quantity of storage to occur within the channel. For Lower Marcombe Lake, there is a 120m channel section between gauges 3 and 4, where the river channel is approximately 1.5m wide. Therefore, for 452m^3 of storage to occur during the largest recorded event, this would assume there was on average a water depth of 2.5m within the channel. As with Upper Marcombe Lake, this is highly infeasible, as the maximum recorded stage was <0.5m.

These high recorded storages at both study sections may be justified by the occurrence of substantial floodplain storage, although the extent to which this occurred is not certain. For both Upper and Lower Marcombe Lake, there are sections of floodplain, extending to >10m across, which may offer substantial flow storage. As an example, if storage did occur across the floodplain, across a width of 10m at high flows, this would equate to 600m^3 of floodplain storage, assuming a 0.5m recorded stage at gauge 2 or 4. However, detailed channel and floodplain bathymetry surveys would be required to justify this and to provide evidence for those quantities of localised floodplain storage. In addition, onsite visits following large, recorded winter events, did not show any substantial evidence of the occurrence of extensive floodplain connection (eg. across a 10m width), for instance through the deposition of vegetation and sediment. This highlights the limitations of assuming system total flow storage from extrapolated discharge data, where rating curve uncertainties may substantially limit the accuracy of the extrapolated high flow values. A complete rating curve for each gauge using field-measured observations (no extrapolation) would be highly advantageous for ensuring confidence in the flow data produced and thus the subsequent analysis of the impacts of woody dams on peak flows. Measuring the highest flows (through stage-discharge measurements) was highly challenging in the field due to the flashy nature of the site where the highest recorded levels receded within minutes of the peak. In longer-term, more established projects, flow meters or fixed cross sections have been installed in-channel, which have presented a robust installation to ensure a complete rating curve (eg. Puttock *et al.*, 2021).

In addition, whilst events have shown marked peak flow reductions downstream of leaky woody dams during high peak events, the contribution of individual dams to these impacts are unclear. From site visits, the dynamic storing function of leaky woody dams across events and in wet periods is evident, which is reflected in flow differences between gauges upstream and downstream of the NFM structures. In the future, such data could be further verified and analysed in-situ by quantifying the dynamic storage volume of the ponds generated immediately upstream of leaky woody dams, through regular, pond surveys and volume monitoring. Finally, a control site to benchmark these results against may be beneficial to act as a comparison, whereby two similar systems are presented, but one with leaky woody dams and the other a channel without interventions. Subsequently, the differences in flows, storage and timings metrics could be analysed. It is important to note that presenting a control reach does introduce additional uncertainties, not least that it would be very difficult to conclude that the two channels (eg. Marcombe Lake, and a control) are identical enough to compare.

4.6. Conclusions

The analysis of two sections of leaky woody dams in a headwater channel in the Tone catchment, SW-England has revealed their potential to attenuate downstream flows. This is demonstrated through peak flow reductions downstream of leaky woody dams during high magnitude events. System spilling following event peaks is markedly slow for many events, occurring in the latter stages of event recession limbs and typically also after the end of the separated flow event. This reflects an elevation of baseflows downstream of leaky woody dams, which is notable particularly during wet periods (where events present high API values). Based on previous research, these attenuating impacts are attributed to the ponding and release of water behind dams and flow onto and off the floodplain during and after events due to floodplain reconnection. The slow release of water following events is reflective of the leaky nature of leaky woody dams.

Whilst there is high confidence in the literature regarding the role of large wood in river channels, current evidence detailing the hydrological impacts of introduced leaky woody dams, deployed as NFM measures, is highly limited and variable. The dataset produced in this chapter acts as a contribution to the empirical evidence base, to detail the local impacts of newly deployed leaky woody dams. In addition, it may also be used as observational data to improve understanding of the impact of leaky woody dams further downstream and for flood risk at the larger spatial scale, through applications within modelling frameworks. Modelling the impacts of leaky woody dams for flood risk reduction is an area of high uncertainty in the literature and further study is required that can extend frameworks to assess the impact of leaky woody dams at further catchments, to consider different scales, land uses and monitored storm events.

4.7. Appendix

This appendix presents the dates and key metrics of 57 analysed events for Upper and Lower Marcombe Lake, where ERD = Event rainfall depth (mm), EP = Event peak (m^3/s), ER = Event rise (m3/s), ED = Event duration (presented as hours: minutes).

			Upper Marcombe Lake				Lower Marcombe Lake			
			Gauge 1		Gauge 2		Gauge 3		Gauge 4	
Date	ERD (mm)	ED (hrs)	ER (m^3/s)	EP (m^3/s)	ER (m^3/s)	EP (m^3/s)	ER (m^3/s)	EP (m^3/s)	ER (m^3/s)	EP (m^3/s)
05/02/19	20.9	05:00	2.19	0.08	0.93	0.06	3.35	0.12	2.53	0.12
09/02/19	19	12:16	2.14	0.12	1.93	0.08	5.67	0.22	3.41	0.16
05/03/19	45.6	20:30	3.76	0.10	2.20	0.07	4.84	0.15	3.80	0.13
12/03/19	22	12:31	2.17	0.08	1.40	0.06	2.52	0.12	2.92	0.12
14/03/19	25.6	11:01	2.47	0.09	1.56	0.07	3.97	0.16	2.28	0.12
16/03/19	19.5	13:30	2.16	0.09	1.10	0.06	2.96	0.16	2.08	0.13
08/05/19	38.4	07:31	3.50	0.10	3.18	0.08	4.74	0.12	5.41	0.13
08/08/19	62.2	08:46	3.92	0.09	2.48	0.06	20.08	0.41	14.58	0.30
16/08/19	43.6	14:01	1.78	0.04	1.17	0.03	5.72	0.14	8.27	0.21
28/09/19	47	19:00	3.03	0.08	2.13	0.05	4.04	0.11	4.59	0.13
05/10/19	23	13:31	2.31	0.06	1.85	0.06	2.76	0.09	5.89	0.15
09/10/19	21	14:16	1.36	0.05	0.94	0.04	0.96	0.06	2.58	0.11
10/10/19	29.2	06:16	5.11	0.12	3.76	0.10	13.15	0.29	10.70	0.25
26/10/19	25.2	06:46	2.26	0.08	2.23	0.08	7.34	0.20	4.47	0.16
30/10/19	51.8	18:01	3.29	0.08	3.36	0.08	8.33	0.19	5.53	0.15
01/11/19	9.4	06:45	1.20	0.07	1.14	0.06	4.27	0.18	2.23	0.11
02/11/19	26.3	12:30	1.57	0.07	2.28	0.08	5.54	0.18	2.35	0.13
09/11/19	28.4	16:00	3.47	0.08	2.73	0.07	6.77	0.18	4.69	0.14
13/11/19	15	02:01	2.46	0.07	2.36	0.07	5.68	0.17	3.86	0.14
14/11/19	20.9	10:30	1.48	0.06	1.52	0.07	3.97	0.14	2.36	0.12
21/11/19	83	45:46	3.60	0.09	6.61	0.15	8.97	0.22	5.78	0.16
08/12/19	26.4	16:16	3.05	0.07	4.01	0.10	5.38	0.16	2.87	0.10
12/12/19	52.2	28:31	5.75	0.13	7.59	0.16	16.06	0.36	7.25	0.19

19/12/19	52.4	20:16	20.19	0.43	14.22	0.30	26.07	0.58	17.10	0.39
24/12/19	15.8	05:16	2.18	0.06	1.04	0.05	3.28	0.13	2.50	0.12
26/12/19	50.1	23:00	7.92	0.15	4.39	0.11	14.17	0.33	8.71	0.23
09/01/20	24.6	06:31	6.28	0.14	3.89	0.09	10.91	0.25	7.21	0.20
13/01/20	16.2	03:15	2.88	0.08	1.85	0.05	4.99	0.14	3.68	0.13
14/01/20	29.4	15:31	2.57	0.07	1.74	0.05	4.46	0.13	2.28	0.11
16/01/20	43.1	06:30	11.85	0.25	7.08	0.15	18.38	0.42	12.70	0.30
28/01/20	16	14:46	1.63	0.04	1.04	0.03	1.99	0.07	1.79	0.07
02/02/20	19	07:15	1.51	0.03	0.85	0.03	1.04	0.06	0.69	0.05
09/02/20	34.8	34:31	1.47	0.03	0.56	0.02	1.39	0.05	0.64	0.04
12/02/20	46	13:16	10.58	0.20	3.89	0.09	9.32	0.21	8.14	0.19
14/02/20	55.6	31:16	8.79	0.19	3.37	0.09	7.89	0.20	6.96	0.19
16/02/20	23.8	11:31	3.18	0.10	1.23	0.06	3.36	0.14	1.86	0.12
24/02/20	17	06:01	2.49	0.07	1.29	0.05	3.73	0.14	2.84	0.11
27/02/20	21.2	08:01	3.08	0.08	1.65	0.05	5.15	0.17	3.28	0.14
28/02/20	58.9	28:00	13.65	0.28	6.20	0.14	17.43	0.41	12.16	0.29
01/03/20	9.6	02:46	1.93	0.07	0.73	0.05	3.72	0.17	1.12	0.13
05/02/20	23	07:01	5.71	0.13	2.92	0.08	9.73	0.27	6.26	0.19
09/03/20	26.6	18:31	1.94	0.06	0.70	0.04	2.49	0.11	0.34	0.08
13/03/20	16.8	08:16	2.07	0.06	1.26	0.05	3.84	0.13	1.01	0.09
15/02/20	33.2	06:01	10.81	0.22	5.79	0.13	16.62	0.39	10.01	0.26
18/06/20	71.2	34:30	2.77	0.07	1.32	0.04	1.27	0.06	1.22	0.07
25/07/20	60.7	08:00	3.59	0.09	2.23	0.06	2.22	0.07	10.64	0.23
19/08/20	63.7	18:15	3.94	0.09	1.99	0.06	4.99	0.13	4.42	0.12
24/08/20	42.6	05:00	4.04	0.09	1.95	0.05	4.45	0.12	5.68	0.14
24/08/20	35.2	09:01	3.33	0.10	1.98	0.06	4.63	0.14	7.19	0.17
02/10/20	87.2	47:31	4.33	0.11	2.61	0.08	6.79	0.17	7.30	0.17
04/10/20	27.6	12:30	2.76	0.11	1.95	0.08	4.49	0.18	6.24	0.19
06/10/20	17.8	13:45	1.19	0.08	0.49	0.06	1.88	0.12	3.15	0.15
07/10/20	17.2	15:46	1.68	0.07	1.16	0.06	2.41	0.13	3.80	0.16
21/10/20	60.2	26:45	10.75	0.25	9.45	0.21	24.52	0.56	15.63	0.35
24/10/20	21.2	09:00	1.71	0.07	1.35	0.07	1.81	0.08	0.86	0.06
11/11/20	22.4	04:31	5.27	0.13	3.50	0.10	8.55	0.21	9.61	0.21
14/11/20	31.4	13:16	5.28	0.16	5.07	0.13	12.37	0.29	6.13	0.15

5. The function and impact of managed online water storage ponds for slowing the flow

5.1. Context

Research Question 3: What is the role and impact of online water storage ponds for slowing the flow, based on the effects of structural design, management, and rainfall events for storage?

There is an uncertain boundary between flood management measures that have a harder engineering design, and those that follow a more 'working with natural processes' framework, a key example being online water storage ponds. As a result, online storage ponds have not been widely considered within NFM review literature, despite their inclusion within UK NFM schemes. There is a need for quantified evidence of their design, function, and potential to store and slow the flow. This should include knowledge of the key inputs and impacts for how they may store water, based on their management and response to rainfall events. This research chapter studies an online water storage pond site in the Parrett catchment, Somerset. Pond volume and rainfall was monitored over a two-year programme and the management conducted by a local flood warden group was recorded in conjunction. This chapter aims to assess the inputs, impacts and wider implications of pond structure, design, management, and hydrological inputs on its ability to store flow across a range of rainfall events.

5.2. Introduction

A substantial range of NFM measures have been considered within review literature and have deployed throughout the UK in recent years (eg. SEPA, 2015; Ngai *et al.*, 2017). These markedly vary between those that follow a very close 'working with natural processes' framework and thus directly emulate naturally occurring features (eg. leaky woody dams) and those that are constructed with substantial quantities of introduced material and hard engineering (eg. constructed storage ponds). In continuation from this, it is important to note that defining what constitutes a NFM structure is not always clearcut. As a result, NFM measures that require a larger amount of hard engineering materials are often referred to in a traditional flood management context, despite an application and documentation within NFM projects across the UK in recent years (eg. SEPA, 2015; FWAG-SW, 2018).

Online water storage ponds represent a key example of a NFM measure that has not conclusively been categorised within NFM literature. Online ponds involve in-channel excavation to generate larger storage quantities, to slow and store flow. Through their design, they are likely to require some hard engineering equipment and materials, such as heavy machinery for initial excavation and PVC pipes for outflow mechanisms. They substantially differ from other in-channel NFM features, such as leaky woody dams (see chapter 4), that are closer to a 'working with natural processes' framework as they are designed to directly emulate naturally occurring wood accumulations in the channel (Gurnell *et al.*, 2019).

The unclarity regarding their categorisation for NFM is also driven through the lack of current resolution in the classification of reservoirs (Ngai *et al.*, 2017). Currently, this is dependent on their individual storage capacity (reservoirs are classified >25000m^3), however there is current uncertainty whether future distributions or cascades of online storage ponds features, with an overall storage capacity exceeding 10000m^3, may need to comply with the Reservoirs Act, which will have design and financial implications for future NFM schemes (Wilkinson *et al.*, 2019). Due to their smaller size (than potentially relatable TFM water storage structures), an optimum scenario for catchment-based flood management may be to have a series of such structures spread throughout a watershed to store flow throughout the landscape (Wingfield *et al.*, 2019).

To highlight the first key research gap of this chapter, to date no empirical studies were identified that specifically evaluate the function or impact of online water storage ponds for NFM. A small number of studies that have applied modelling techniques to evaluate the impact of other NFM features to generate in-channel storages were identified (eg. Nicholson *et al.*, 2012, 2019; Metcalfe *et al.*, 2017). However, limited information could be located that has assessed the key controls and impacts of online water storage ponds in response to rainfall events and thus justify or analyse their current inclusion with UK NFM schemes.

The second key research gap to be targeted in this chapter is the high lack of certainty regarding the maintenance requirements of NFM, including what management plans should include and the frequency, intensity and impacts of NFM maintenance (Ngai *et al.*, 2017; Burgess-Gamble *et al.*, 2018; Wells *et al.*, 2020). The collaboration and catchment-wide stakeholder interaction that is widely associated as essential for NFM success (eg. Howgate and Kenyon, 2009; Mehring *et al.*, 2018; D'Souza *et al.*, 2021), implies that management and maintenance are more complex for NFM than processes practiced through TFM due to the variety and quantity of land uses and landowners involved (Wilkinson *et al.*, 2019). The European Commission Natural Water Retention Measures (NWRM) initiative states that NFM maintenance costs are typically up to 1.5% of the initial construction costs, however this is based on minimal UK case studies and empirical evidence (Ngai *et al.*, 2017). Indeed pilot UK studies have highlighted that NFM schemes expect to be self-sustaining, requiring minimal maintenance and management, which can occur within existing agricultural practices (eg. Old *et al.*, 2018). However, there are a lack of case study examples and evidence to understand the likely maintenance and materials required and the lifespan of structures (Old *et al.*, 2018; Wilkinson *et al.*, 2019).

This second key research gap of this chapter is particularly applicable for online water storage ponds compared to other NFM features, as they are likely to require marked levels of management and maintenance due to their larger size, use of hard materials and design that is relatively complex, where total storages can be directly controlled through the use of outflow mechanisms. Therefore, as the storages held by online ponds can be directly controlled by humans, their management could feasibly have the potential to alter their attenuation efficacy as much as rainfall events.

Therefore, in response to these two key research gaps, it is important to examine the effects of management, as well as rainfall events to fully understand the impact of online water storage ponds for storing flow, to thus function as designed (Black *et al.*, 2021). The improvement of knowledge transfer is vital for future consideration of all potential NFM structures for future implementation (Newson *et al.*, 2021).

Therefore, in this chapter, two online water storage ponds in the upper Parrett headwaters, in South Somerset were monitored between November 2018 and December 2020, where high-resolution pond volume, rainfall, management, and maintenance log datasets were collected. These features were constructed in response to local flooding issues downstream in the winter of 2013/14 and were constructed to hold back water behind controlled outflow sluices, which are managed by a local flood warden group. Firstly, the function of the online storage ponds is examined, by assessing the role of two key controls on pond storage: the structure (based on pond design, capacity, and outflow mechanisms), along with the hydrological inputs monitored (event rainfall and antecedent conditions). Secondly, the impacts of online ponds for storage and slowing the flow are examined by assessing the role and effects of management and rainfall events. The impacts of management are assessed according to a series of success criteria for events across the monitoring period. In addition, the impacts of rainfall events are assessed by extracting key timing metrics from the monitored pond volume data. Events are separated according to key management scenarios to importantly compare the role of rainfall events versus system management in determining the ability and efficacy of online storage ponds to slow the flow.

5.3. Methodology

5.3.1. Study area and installations

Two online water storage ponds were studied between November 2018 and December 2020, at ‘Wellhams’: an upper headwater site (upstream catchment area of $1km^2$) in the Parrett catchment, Somerset (SW-England). The ponds are situated in the valley of an apple orchard farm, with a mean annual rainfall total of 776mm. In line with NFM structures introduced in chapter 2 and analysed in chapters 3-4, these measures were established to contribute to a wider scheme aiming to slow and store flow in headwater catchments in Somerset, through the Hills to Levels project. An Orthomosaic of the study site, depicting Wellhams, along with the locations of ponds, gauges and outflow structures and corresponding images is shown in Figure 5.1.

The online ponds are fed by a small channel that flows from upstream springs (see Figure 5.1a) and are both controlled via separate outflow sluices. These both have a lower sluice gate (150mm diameter for upstream pond and 300mm for downstream pond), that can be opened or closed. In addition, they were constructed with a higher overflow pipe (300mm diameter). Both of these outflow pipes combine together in a ‘T’ junction for the upstream pond (see Figure 5.1b) and an outflow cylinder for the downstream pond (see 5.1e) and are released via an outflow pipe (see Figure 5.1c). For the upstream pond, this releases flow into a field channel that runs between the two ponds (see Figure 5.1d) and for the downstream pond, this releases water out of the NFM system (see Figure 5.1f).

The two ponds were developed from two existing in-channel ponds at the site. The downstream pond was refurbished and enlarged in 2017, with a sluice controlled installed. In 2018, the pond was further enlarged to its current capacity. The upstream pond had an outflow sluice installed on the existing pond in 2018. Construction and subsequent management and maintenance funding has come from the EU funded projects and the Somerset Rivers Authority (SRA). The ponds are managed by local flood wardens, with all site work conducted by the flood warden team, the landowner, and contractors.

Figure 5.1. Orthomosaic (produced from drone SfM DEM) of Wellhams online ponds (Parrett catchment). Images correspond to key aspects: springs and channel upstream of the upstream pond (a), upstream pond outflow sluice (b), outflow pipe that drains from the upstream pond (c), field channel between the two ponds (d), downstream pond outflow sluice (e) and outflow pipe that drains from the downstream pond (f).

The general monitoring setup is described in chapter 2 (section 2.5). Briefly, a HOBO RG3-M tipping bucket rain gauge was installed adjacent to the upstream pond. Stage was recorded using HOBO U20L-01 (Onset, 2014) water level loggers, which were encased within stilling wells and installed in the deepest section of each pond. A stage-volume rating was established from DEMs (see Figure 5.2), produced from drone SfM and manual methods (see chapter 2, sections 2.5.2 - 2.5.4).

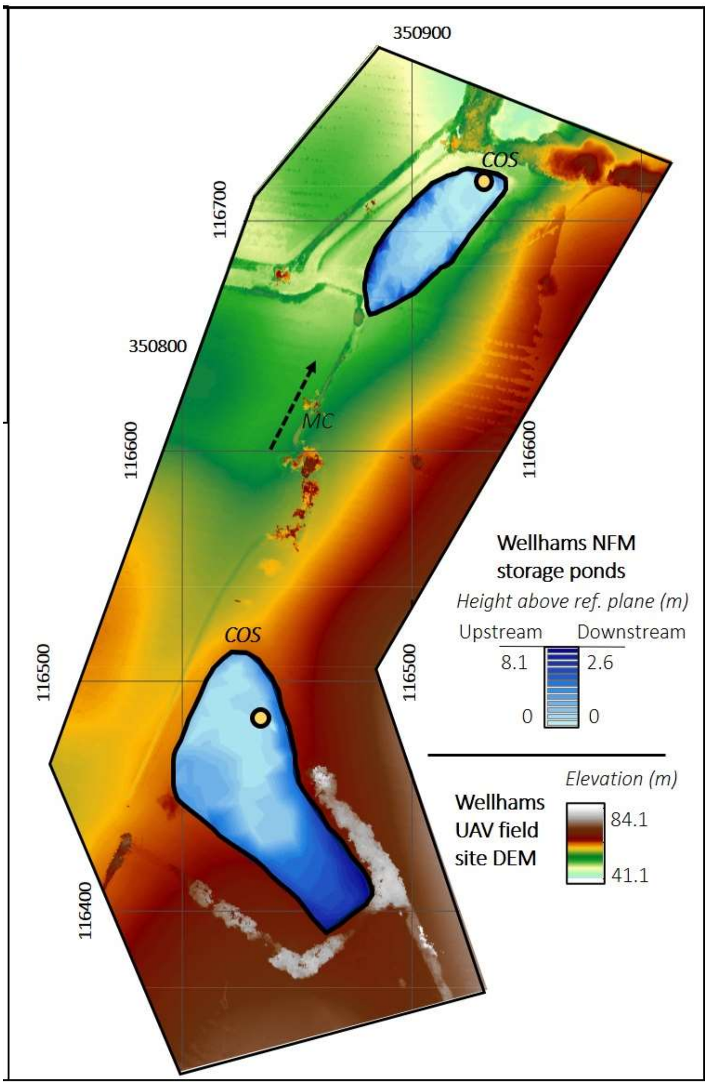

Figure 5.2. Wellhams DEMs, produced from drone SfM methods. Pond DEMs, generated using manual methods are overlain, illustrating height from a reference gauge (0m) for stage to volume conversions. Elevation refers to metres above sea level. Detailed are controlled outflow structures (COS), main channel (MC) and pond gauge locations.

5.3.2. Issues with calculating flow data at Wellhams

An important addition to this methodology section is to document where issues arose with the original methodology plans. Initially, system inflows and outflows were to be calculated based on pipeflow measurements and calculations to gain system flow data. The following section will detail the original methodological plan for this, a brief summary of the methods conducted, the issues found and then subsequently the steps taken instead. These issues are detailed to highlight the key challenges and limitations of the methods conducted in this chapter and provide context for the subsequent approach taken to analyse hydrological metrics.

To gain system inflow and outflow values, it was initially assumed that all flows could be accounted for by estimating their values from pipeflow equations and known measured heights in the two ponds. This is importantly based on the assumption that all flow passing through the upstream pond outflow pipe, later passes through the downstream pond outflow pipe. In addition, this also assumes that all pond volume decreases are also contributing directly to system outflow. Therefore, to present an example of these assumptions if the downstream pond volume is decreasing by 5m^3/min and there is 0m^3/min inflow into the downstream pond from the upstream pond (eg. upstream pond outflows have been recently shut and levels are too low for any outflow), the system outflow must be 5m^3/min. Taking into account these assumptions, system inflow (channel inflow upstream of the upstream pond, see Figure 5.1a) was calculated as upstream pond volume change (m^3/min) + upstream pond pipeflow (m^3/min). System outflow (see Figure 5.1f), was calculated as downstream pipeflow (m^3/min).

Therefore, to gain system inflow and outflow, pipeflow leaving the upstream pond and downstream pond needed to be calculated for each minute of the monitored time series. The water level gauges in each pond and the outflow pipe heights were surveyed using an OS Total station to gain accurate heights (relative to a 0m marker). Then, the pond levels at which pipeflow is expected were recorded. Two different pipeflow equations were used: Darcy Weisbach for full pipeflow and Manning equation for partially full pipeflow. A workflow was developed in MATLAB (2019b) to process the needed pipeflow equation for each pond level and outflow scenario (open/closed/half). Table 5.1. illustrates the pond level thresholds, pipeflow expected and equation used.

Using these stated rules, the workflow was executed for the upstream and downstream pond levels to gain upstream pond and downstream pond pipeflow. Downstream pond pipeflow was used to directly gain system outflow and upstream pond pipeflow was summed with upstream pond volume change (m^3/min) to gain system inflow.

		Level (m)	**Pipe**	**Equation**	**Time series %**
Upstream	**Open**	<0.5	No flow	No equation needed	1.74
		0.5-0.8	Partially full pipe	Manning's	23.44
		>0.8	Full pipe	Darcy Weisbach	74.82
	Closed	<1.4	No flow	No equation needed	42.39
		1.4-1.7	Partially full pipe	Manning's	51.49
		>1.7	Full pipe	Darcy Weisbach	6.13
Downstream	**Open**	<0.14	No flow	No equation needed	3.57
		0.14-0.44	Partially full pipe	Manning's	42.86
		>0.44	Full pipe	Darcy Weisbach	53.56
	Closed	<1.25	No flow	No equation needed	90.52
		1.25-1.55	Partially full pipe	Manning's	8.6
		>1.55	Full pipe	Darcy Weisbach	0.87

Table 5.1. Key criteria for all water level scenarios in the time series, to select which equation should be used, based on the recorded water level and whether outflow is open, half or closed. Level (m) refers to water level (stage) recorded by each respective in-pond logger. Time series % indicates the percentage of the time series that each scenario is applicable for. No equation is required for levels <0.5m (upstream) and <0.14m (downstream) as water has not reached the height of the main sluice outflow pipe and thus no outflow should be occurring.

Following the execution of the stated methods, it was found that even within the uncertainty boundaries stated (eg. altering slope values of both equations within reasonable limits), summed system inflows were either hugely more than or less than outflows within a reasonable time scale, and with consideration to the cumulative stored flows within the ponds. Whilst some discrepancy in values was anticipated, the complete lack of regularity in where inflows were larger or small than outflows made taking these values (eg. using for analysis) any further unfeasible as so many uncertainties would be introduced to the results. There may have been a number of reasons for these system inflow and outflow calculated differences over time, perhaps most likely unmeasured water inputs and storage losses from throughflow. This perhaps highlights that the assumptions made about system inflows and outflows are not as tangible as first assumed.

In hindsight, the installation of level gauges upstream and downstream of the pond system would have been the most ideal scenario (where stage-discharge ratings could have been produced, in line with the methods described in chapter 2, section 2.5). At the start of the project, financial considerations resulted in the above methodology being planned instead of additional gauge installations. Ultimately this unfortunately did not result in flow data being produced for this chapter on account of issues that could not be resolved within the timescale of this project.

In response to these issues, the methodology of this chapter focussed on the impacts of rainfall events on pond volume storage, where rainfall events were separated according to in-channel storages. Whilst this did not offer the inflow to outflow comparisons planned, it still enables comparison of key processes and factors that are specific to this NFM sites, including the impact of rainfall events on storage volumes and the inputs and impacts of outflow management on pond function.

5.3.3. Rainfall event definition

To examine the full range of events captured during the monitoring period, the event definition methodology introduced in chapter 2 (section 2.5.6) was used to separate individual rainfall periods and the corresponding pond volume data. In contrast to the application of this event definition workflow in chapters 3 and 4, where flow data was used, certain adaptations were required for this methodology to work for the volume data collected at Wellhams. Firstly, in contrast to where flow data was used at Halsewater, Merriott and Marcombe Lake (chapters 3-4), no return to pre-event conditions was required for the events to be used for analysis. Where flow (in-channel) data was used, a return to baseflow (within a 10% threshold) was deemed highly feasible for the majority of events. The few exceptions to this were not used for analysis as a complete hydrograph was required for full event volume assessment. In contrast, for pond volume data analysed at Wellhams, the dynamics are more complex where filling and spilling is not solely controlled by hydrological inputs (eg. rainfall and catchment runoff). Indeed, control of the pond outflows (eg. opening and closure) mean that high pre-event volumes are feasible and unequal quantities of filling and spilling within an event period are likely particular where one or both outflows are closed. Moreover, as of particular interest in this chapter are the different factors that control overall pond attenuation (including management of outflows, along with event rainfall), removing events that don't generate a 'complete' hydrograph would actually remove key samples of interest.

On this note, all events (rather than the top 30% magnitude applied in chapters 3 and 4) were extracted for analysis as pond storage was anticipated to be dependent on outflow opening and closing, as well as hydrological factors such as the event rainfall depth. Therefore, examining all separated events was advantageous to fully consider the impact of management on pond function. Only a small number of events were not included for analysis where outflow management was changed during the event and as a result categorising the event type (eg. an open or closed event) would introduce added complexities. This was only the case for 12 events, all of which had small event rainfall depths (<7mm).

5.3.4. Hydrological metrics

To examine the impact of the extracted rainfall events on pond volume, storage timings and deemed efficacy (within the constraints by the issues highlighted in section 5.3.3) to slow the flow, two hydrological metrics were extracted from the volume data. Here, the rationale and methods used to extract the start of rainfall to start of pond response lag time, and secondly, the upstream to downstream pond peak travel time are presented.

Event API

Antecedent conditions were considered as a potential key control on pond storage during events and seasonally. Thus, for the rainfall data captured, antecedent conditions were quantified by calculated the API value for each day (eqn. 1), representing accumulated rainfall over time. API increases with additional rainfall (P) and declines where there is no new rainfall, according to a decay constant (k) of 0.9 (Heggen, 2001; Ali *et al.*, 2010). This corresponds with the approach taken for sites studied in chapters 3 and 4, where event API was extracted as the value for the day of the event start.

$$API_d = kAPI_{d-1} + P_d \qquad \text{eqn. 1.}$$

Pond volume event rise and peak

Pond volume event rise and peak were considered in this chapter as key indicators of the effects of pond structural controls, principally if outflows are open or closed and the impacts of this on the event pond peak and volume rise, along with the relationship between these two metrics. This was important to highlight the impact of pre-event pond volumes on event peaks (alongside the impact of structural controls), for example including the extent to which low event pond volume rises results in a low pond volume peak. This enables an examination of the impact of structural (eg. outflow open/closure) and hydrological (eg. event rainfall) on pond storage.

The time of peak volume at the upstream pond and downstream pond was obtained systematically for each event by extracting the highest value between after the defined event start but 2 hours before the start of the next separated event. These were then verified by visually examining the time series data to ensure the pond volume peak instigated by rainfall was selected, and not a later peak generated by changes to the outflow (eg. later opening of outflows causing an additional downstream pond peak volume).

Subsequently, the pond volume event rise was extracted for the upstream and downstream pond as the difference between the pond volume value obtained at the event start and the highest recorded event value (peak volume).

Start of rainfall to start of pond response lag time

The pond response time is extracted as the time between the start of event rainfall and when pond volumes start to rise. The speed of this response time is considered an indicator of the attenuating impact of the upstream pond on the downstream pond volumes. For example, if the upstream pond is attenuating flow and there is a delay to water stored in the upstream pond reaching the downstream pond (eg. stored behind the outflow, where levels do not reach the overflow pipe until part way through the event), a longer pond response time in the downstream pond (compared to the upstream pond) is expected. To consider open and closed outflow events separately, here the impact of outflow closure (high pond volumes required before any outflow from either pond) on pond response time is also considered.

It is important to note that this metric does not offer the same insight as if inflow and outflow data were to be used (see section 5.3.3). However, by extracting these lag time values for pond volume data, this provides an indication of the impact of open versus closed outflow events and of upstream and downstream pond responses. Pond responses can be expected regardless of whether outflows are open or closed as if inflows are high enough, water levels are expected to rise above the main sluice or overflow pipe, where outflows are thus exceeded by the incoming flows. The start of pond response time is extracted as the 5th percentile of the pond volume rising limb. The rising limb is defined as the 5th-95th values from the start of pond response time to the event peak (highest pond volume value). The start of rainfall to start of pond response lag time is subsequently extracted as the time difference between the event start (first occurrence of regular rainfall, see chapter 2 (section 2.5.6), and the time of the 5th percentile of the rising limb.

Upstream to downstream pond peak travel time

An increased upstream to downstream pond peak travel time may be expected if a marked quantity of flow volume is stored within the online ponds. It is important to note that this is not expected to present the same indication of travel time and lag as if system inflows versus outflows (or even stage) were examined (eg. Kitts, 2010; Wilkinson *et al.*, 2010b; Thomas and Nisbet, 2012; Black *et al.*, 2021). The benefit of considering flows would mean that a direct indication of system attenuation can be gained, as based on control reaches or estimated expected flow travel times (if ponds were not constructed), the impact of NFM features for increasing (or decreasing) lag times can be extracted. However, for this site, pond volume data was used to gain an indication of the complexities of storage behaviours across rainfall events and the impacts of events on attenuation. This also importantly separates open and closed outflow events to examine the impact of pond structure and mechanisms, alongside the hydrological inputs during events.

The pond peak travel time was calculated as the time difference between the extracted peak time of the upstream and downstream pond. If flow data was used, this would be expected to always be a positive value (as peak flows are transported downstream). However, as volume data is used here, the impacts of in-channel storage change, potential forced volume increase behind outflows, and the difference in overall capacity between the two ponds mean that negative travel times are also feasible. This would occur where the upstream pond volume reaches its highest value after the downstream pond. This is feasible particularly if the downstream pond's capacity is higher than the upstream pond prior to the event (likely as the potential capacity of the downstream pond is 1129m^3 larger than the upstream pond). This may mean that the downstream pond reaches the peak faster and outflow occurs through the downstream pond overflow before upstream pond levels reach the upstream pond overflow and thus any upstream pond recession can occur.

5.3.5. Criteria for effective online water storage pond management

Wellhams online water storage ponds are managed and operated by a team of volunteer flood wardens that actively manage the site and others locally as a Community Flood Group (CFG). This represents an example of 'bottom-up' flood management, which has expanded alongside the adoption of catchment-based approach through the expansion of NFM projects in recent years (Mehring *et al.*, 2018). This relies on stakeholders throughout the catchment for scheme inception, promotion, confidence and future success (Howgate and Kenyon, 2009; Short *et al.*, 2019). The management of NFM by a CFG offers many advantages for NFM success as it brings a particular focus on community engagement and landowner cooperation, introducing local knowledge and cooperation (Old *et al.*, 2018; Ferguson and Fenner, 2020a; Garvey and Paavola, 2021; Newson *et al.*, 2021). Community-based NFM has highlighted the importance of catchment-wide coordination, to utilise different land uses and measures to store and slow flow (Waylen *et al.*, 2018; Connelly *et al.*, 2020; D'Souza *et al.*, 2021), whilst also gaining wider benefits, such as habitat creation and pollution control (Black *et al.*, 2021).

The tasks of the flood warden team centre around the management of pond storage, including outflow opening and closing and organising maintenance. Figure 5.3 presents a series of images that detail the impacts of outflow closure and opening for pond storage and water levels relative to the respective outflow sluices, where ponds are functioning correctly (eg. there are no faults). When pond outflow sluices are kept closed and during 'non-event periods', pond levels are relatively constant at the bottom of the overflow pipe of both ponds. When pond outflow sluices are kept open, water levels are generally steady at the lower outflow sluice gate. This equilibrium is due to small steady inflows from upstream springs.

The following section presents the key operational objectives for pond management and corresponding success criteria, based on the key tasks carried out by the flood warden team, conducted to optimise the potential of ponds to store and slow floodwater, and the expected impacts. These success criteria also consider where tasks may need to be adapted to respond to factors out of the volunteer flood warden's control, such as mechanism faults and the infeasibility of conducting very frequent site visits. The tasks and success criteria are based on information and guidance from the flood warden team and FWAG-SW. These criteria are separated into the following five key tasks and are summarised by Table 5.2.

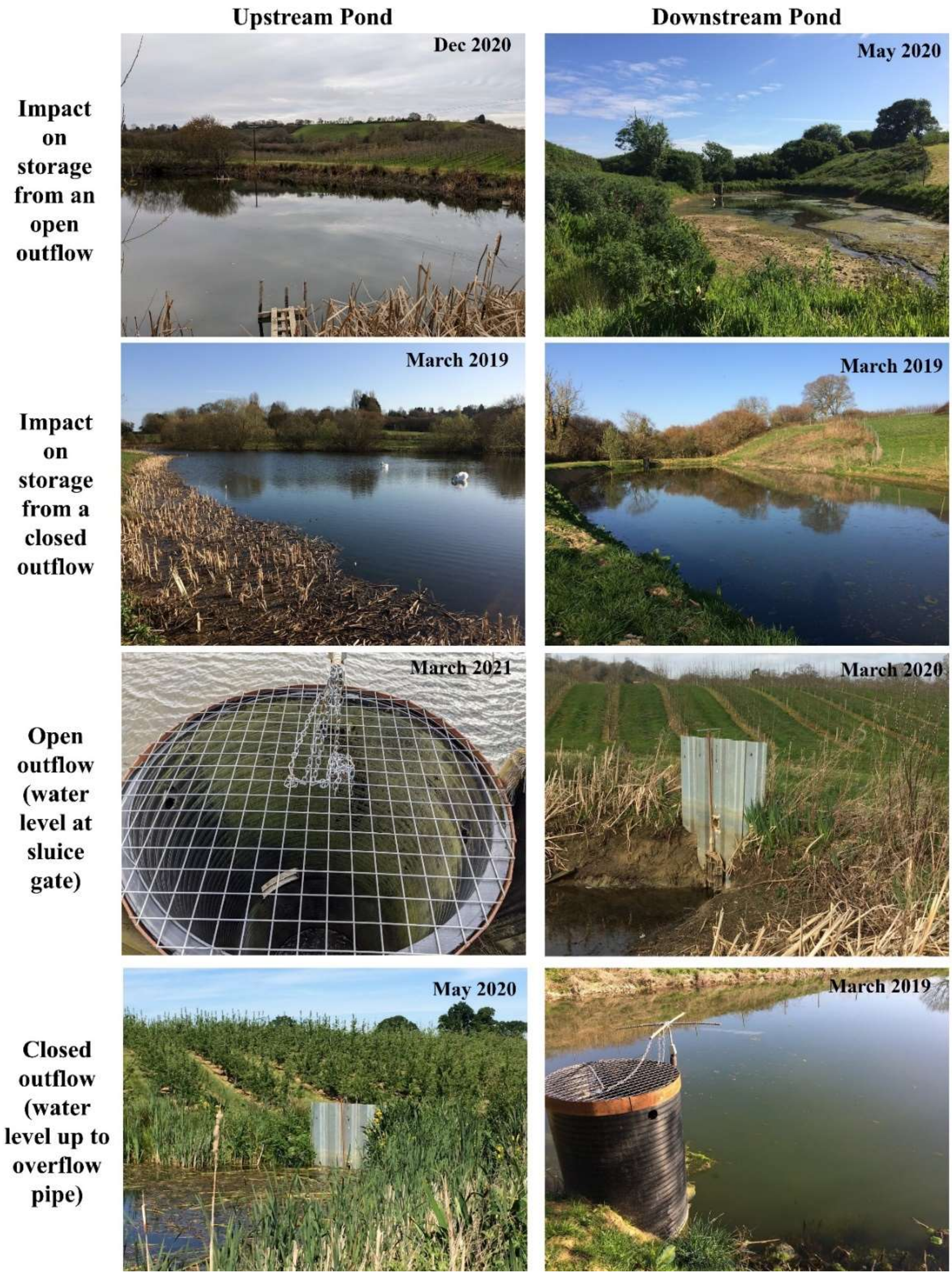

Figure 5.3. Expected impacts of outflow management on pond storage and water levels from open outflows (level up to main sluice gate) and closed outflows (level up to overflow pipe).

1. Maintain a low pond volume storage prior to large, forecasted rainfall events
2. Close outflows immediately prior to large rainfall events
3. Open outflows after large rainfall events
4. Maintain a high pond volume storage during periods of low rainfall
5. Secure maintenance works on the ponds where required

A log was kept of all management and maintenance, including opening, closing and repairs, the rationales for all actions and any wider impacts (eg. reported pond overtopping). For each event, the applicability of each task was considered, for example where tasks 1-3 may be appropriate for one event, but only task 5 may be appropriate for another event. Then, the appropriate, chosen tasks for each event were assessed according to the stated success criteria. The success of each task for facilitating the ponds to function optimally was assessed by categorising each task for each appliable event as a 'success', 'adjusted success' or 'no success'. 'Success' was used where the task was conducted in line with the presented success criteria, where no problems were encountered. 'Adjusted success' was used firstly where feasibility issues meant that management was not conducted in line with the success criteria, but no additional negative impacts occurred as a result (eg. pond capacities being exceeded). 'Adjusted success' was also used where the innovative actions of the flood warden team worked around issues to best manage the site in specific circumstances. Finally, 'no success' was used where the impacts of the task were not apparent for an event, which may have resulted in local negative impacts, such as farmland flooding from pond overtopping.

Categorising the success of each key task is important to examine how online storage sites can be managed, the impacts of key tasks and to highlight any recurring issues. For example, if a task is categorised as a 'no success' for a particular event, it is important to understand why that was and if there are implications for pond function. This allows for NFM management recommendations to be highlighted based on the successes, constraints, and difficulties of the management of an online water storage pond site in this way.

This information was also used to separate events according to whether pond outflows were closed or open, for study of the hydrological metrics extracted from the pond volume data. This allowed for an examination of the impact of rainfall event versus pond structure and management, on the ability of ponds to store and slow the flow. This was deemed important on account of the anticipated impact of filling and spilling that outflow management (eg.

opening and closing) on total volumes. Without separating events in this way, it would be challenging to decipher whether the results of the extracted hydrological metrics were as a result of even inputs (eg. rainfall) or if they were because of the outflows.

	Task	Events assessed	Success	Adjusted success	No success
1	Maintain low pond storage before large, forecasted winter events	Event rainfall depth is >10mm (above the mean event rainfall total across all events). Between October and March	Low pond volumes prior to large rainfall events	High volumes unavoidable due to consecutive large rainfall events.	High volumes before large rainfall events, despite no recent large events
2	Close outflows prior to large, winter events		Outflows are closed at the start of large, forecasted events	Feasibility issues mean that outflows are closed early	Outflows are not closed prior to large events
3	Open outflows after large, winter rainfall events		Outflows are opened soon after events, especially if ponds are at capacity	Ponds are half-open	Ponds are not opened after large events
4	Maintain a high storage during low rainfall periods	API value <22 Event rainfall >10mm Between April and September	Outflows are closed during periods of low rainfall	Outflows are not closed but for external reasons	Outflows are open during long, dry periods.
5	Secure maintenance on the ponds	Occurred whilst ponds had a fault	Events with faults		Events without faults
			Events with faults that cause additional negative impacts		Events with faults that do not cause additional negative impacts

Table 5.2. Summary of success criteria for key tasks undertaken to aim to maintain full pond function and efficacy. Events assessed indicates the criteria that an event must match in order to be deemed applicable for each task.

Task 1. Maintain a low pond storage prior to large, forecasted winter rainfall events

Firstly, the ponds should have a low pond volume storage prior to large, forecasted rainfall events. As larger rainfall quantities are anticipated during the winter months, the pond outflows are therefore typically kept open from October to March, to maintain a constant lower pond volume. The rationale for this is to allow for as much stormwater filling as possible, to utilise the potential pond storage capacity. If the pond is already nearly full prior to a large event, minimal stormwater can be expected to be stored before spillage occurs through the overflow pipe. Moreover, keeping a low pre-event storage volume reduces the chance that pond capacities will be reached or exceeded prior to the event peak, which could result in local farmland flooding.

For task 1 to be deemed a 'success', low pond volumes were extracted at the start of large rainfall events. A low pond volume was categorised as a total site storage of $<3694m^3$ (< 50% total site storage fullness). Large rainfall events were categorised based on the event having above the mean event rainfall depth of 10mm (based on all separated events).

It is important to note that maintaining a low pre-event capacity in the winter period for consecutive, large rainfall events is not always possible. Indeed, where multiple large events occur within a short time frame, a full pond spillage down to the bottom of the main sluice height (down to 16.4% and 1.5% pond fullness for the upstream and downstream pond, respectively) is unlikely to occur. Therefore, during periods where there are multiple rainfall periods in a short time frame, it should not be expected that low pre-event volumes are going to be achieved at the start of every event. This was categorised where there were >2 large rainfall events (events with rainfall depths > mean across all events) occurring within 7 days of each other and was classified as an 'adjusted success'.

Finally, where a large rainfall event occurs after a marked period of no rainfall (API values fall to <22 (mean API value over the monitoring period), low pre-event pond volumes $<3694m^3$ (< 50% total site storage fullness) are expected. Thus, where they are higher than 50% of total site storage fullness, 'no success' is classified, which importantly may suggest additional issues are occurring, such as an outflow blockage.

Task 2. Close outflows prior to large, forecasted winter rainfall events

Secondly, pond outflows should be closed at the start of large, forecasted rainfall events. This task relies on task 1 being conducted, where outflows are open during the winter months to maintain a low storage capacity in readiness for potentially large events. The rationale for this is to maximise potential storage before any spilling from the overflow outflow pipes. Based on discussions presented in the literature (eg. Thomas and Nisbet, 2012), task 2 aims to desynchronise flood peaks downstream, notably for the village of Martock as flows are expected to be temporarily stored within the online storage ponds, increasing the travel time for peak flows from this system to reach downstream.

For task 2 to be deemed a 'success', outflows should be closed within 48 hours of large, forecasted rainfall events, categorised as those >10mm (mean event rainfall across the monitoring period). Based on typical winter pond management, this also is only applicable to events between October and March.

It is important to note that the execution of this is dependent on the accuracy of forecasted rainfall and also where sites visits can be feasibly made prior to the event. For example, in certain cases it may be possible for the flood wardens to close the outflows within a few hours of the start of event rainfall, if warden time availability allows and with regards to other factors such as this coinciding with daylight hours (necessary for safe site access for the volunteers). However, at other times, outflows closure may only be possible at minimum of a day or 2 prior to the event start. These are important feasibility considerations to make and therefore in these instances, the task is deemed an 'adjusted success'.

To optimise potential pond storage during events and the overall function of the NFM system, it is important to note where this task was not completed (and there were no external feasibility issues). In this instance, this is documented as a 'no success' to reflect where it may not have been deemed necessary to close outflows prior to large, forecasted winter rainfall events.

Task 3. Open outflows after large, forecasted winter rainfall events

Thirdly, pond outflows should also be opened after large winter rainfall events to reduce overall pond storage, in the anticipation of a future large event. This should be conducted in response to task 1, which focusses on maintaining low storages before events and then task 2, which focusses on closing outflows immediately prior to large, forecasted rainfall events. The rationale for this is that it enables storages to be reduced for further filling if large events are expected (see task 2). It also means that the stored flow can be released at a chosen time. By opening the outflows after large events, the stored flow contained within the ponds has not contributed directly to the downstream event peak. By releasing water later, water quantities are instead being added to the event recession or river baseflows.

For task 3 to be deemed a ‘success’, outflows should be opened within 48 hours of large rainfall events (events with total rainfall depths >10mm), in particular following events where ponds have reached 100% capacity. If pond outflows are not opened where needed, this could result in pond capacities being reached and exceeded, resulting in local flooding of farmland. In addition, without opening outflows after large events, this may mean that there are very high pond volumes before subsequent large winter rainfall events, limiting the feasibility of completing task 1.

However, it is important to note that this task may require particularly careful management if one large event is quickly followed by another. In response, outflows may be kept half open when multiple large rainfall events are forecasted, but where the close timing of forecasted events means that the opening and closing of outflows multiple times within a few days is not feasible. These situations are categorised as where there were >3 large rainfall events (events with rainfall depths >10mm) within 7 days. Keeping outflows half-open enables greater spilling than if they are kept open but maintains a greater potential storage than if they are kept closed. In this instance, the task is categorised as an ‘adjusted success’.

Finally, where the criteria for ‘adjusted success’ is not applicable and where outflows are not opened within 48 hours of the event, the task is categorised as a ‘no success’, which as with task 1, may importantly indicate that additional issues are occurring.

Task 4. Maintain a high pond volume storage during periods of low rainfall

Fourthly, Wellhams ponds should be kept closed during periods of low rainfall to maintain a high storage for wider NFM benefits (eg. wildlife). As fewer large rainfall events are anticipated in the summer months, ponds are typically kept closed between April and October. The rationale for this task is to maximise on the wider benefits of the construction of these ponds, principally for habitat creation and shelter for wildlife. At Wellhams, this notably includes habitats for local swan populations. These ponds were primarily constructed to storage and hold back stormwater during large rainfall events and therefore when these rainfall events are not forecasted, it is fitting that the wider benefits that the ponds offer are utilised. Keeping a high pond volume during summer also provides a contingency store of water for the landowner, for potential irrigation purposes. This additional purpose offers an additional incentive for landowner engagement with pond construction and management.

For task 4 to be deemed a 'success', pond volumes must be high during periods of low rainfall, involving the closure of outflows. Low rainfall periods were categorised as firstly to have low antecedent conditions, indicated by the event API value being within the lowest 20% of all API values extracted across the whole monitoring period (an API value of < 22). In addition, the time of year was an important additional factor to ensure regularity for the schedules of the flood wardens. Thus, between April and September each year, pond outflows were typically closed (except where tasks 1-3 were necessary for events) and minimum pond volumes of >2850m^3 (70.6%) and >1300m^3 (43.9%) for the upstream and downstream pond, respectively are expected.

For task 4 to be deemed an 'adjusted success', pond outflows may not necessarily be closed but this would be due to additional reasons, for example the need for low volumes to allow for maintenance works.

If there are low pond volumes when outflows are supposedly closed, this may be an indicator of additional issues occurring, such as a failure of the outflow mechanism and a need for maintenance. Thus, where this occurred, or if pond outflows are open during long, dry periods, this may limit the ponds function to provide wider NFM benefits when not required to store floodwater. In these instances, task 4 is categorised as a 'no success'.

Task 5. Secure maintenance works on the ponds where required

Finally, Wellhams ponds should be maintained, including the completion of any repairs, to ensure their function to both store and release flow where needed is preserved. This requires close management and regular checks on the pond mechanisms. These tasks may be required at any time, but particular attenuation should be paid after the largest events, as bank instability may occur if ponds exceed capacity. Also, if large material has been transported from upstream due to high flows, there is a chance of outflows becoming blocked.

Key identifiers of maintenance being required are where storage is not behaving as expected, based on outflow management. Examples may include where volumes are low, despite outflow closure, or volumes being high outside of event periods despite outflows being open (see Figure 5.3 for visual indications of expected volumes when outflows are open or closed). Visual inspections are also anticipated to be needed, to identify issues in advance, such as potential bank collapse. To understand the extent and impact of pond faults and subsequent maintenance is important as for ponds to effectively store stormwater during rainfall events and for outflow management to be conducted according to tasks 1, 2, 3 and 4, the storage capacity (pond structure) and outflow mechanisms need to be fully operational.

The success of task 5 is assessed in two ways. Firstly, the impacts of faults or issues at the ponds on its function during events was considered by extracting the number of times faults coincided with a separated rainfall event. This assumes that if a fault occurs with the pond, but it does not occur during any periods of marked rainfall, then there are unlikely to be any marked negative implications. This information is important to highlight the proportion of time across the monitoring period where repairs (or other maintenance) were required. For example, if no events were reported to have occurred when repairs were needed, this suggests that maintenance at the site may be less of a major issue for others of similar design. Secondly, of the quantity of events that occurred whilst pond faults or issues were present at the site, the number of rainfall events that resulted in additional negative local impacts were extracted. These additional impacts are largely expected to be local farmland flooding, for instance as a result of outflow mechanism faults and a lack of system drainage. This is important information to consider whether maintenance issues are expected to have negative implications or if their management does not require direct or relatively swift responses.

5.4. Results

To introduce the results of this chapter, the extracted rainfall events from across the monitoring period are firstly presented (section 5.4.1). Subsequently, the function and impact of the managed online water storage pond for slowing the flow is examined, in line with the aim of this chapter. The function of the ponds is studied based on two key controls on pond storage. Firstly, the pond structure: its design, capacity, and outflow mechanisms (including open versus closed), which is presented in section 5.4.2, and secondly, the hydrological inputs monitored: event rainfall and antecedent conditions, which is presented in section 5.4.3. Next, the impact of the ponds is assessed by firstly examining the decision-making of how the pond structure is managed and the outcome for pond storage across rainfall events, based on select success criteria, which is presented in section 5.4.4. Finally, the inputs and impacts of rainfall events for pond storage and efficacy will be examined in section 5.4.5, where events will be separately examined according to key management scenarios (principally where outflows are open or closed).

5.4.1. Separated rainfall events

Firstly, the monitored pond volume and rainfall data and separated rainfall events will be introduced. Across the 26-month monitoring period, 94 events were separated for analysis in total, of which an introduction to the key event characteristics is presented by Table 5.3. In addition, the full monitoring time series is presented by Figure 5.4, illustrating pond volume, pond percentage capacity (pond fullness), hourly rainfall, and associated outflow management (open, half or closed) for both ponds. Volume changes across both ponds are affected and controlled by two key factors: rainfall events, (rainfall inputs and antecedent conditions) and pond structure (design and construction, including whether outflows are open or closed). The two key controls are subsequently examined in sections 5.4.2 and 5.4.3, respectively.

Event characteristic		Value
Total number of events extracted		94
Total number of events with both pond outflows open		34
Total number of events with both pond outflows closed		38
Mean event rainfall (mm)		10
Recorded rainfall range (mm/hour)		0.2 - 8.8
Event rainfall range (mm)		3 - 38.2
Upstream pond volume event rise range (m^3)		0 – 2214
Downstream pond volume event rise range (m^3)		0 - 1541
Upstream pond volume event recession range (m^3)		0 - 1171
Downstream pond volume event recession range (m^3)		0 - 1344
Upstream pond volume event start value range (m^3)		337 - 3963
Downstream pond volume event start value range (m^3)		43 - 3032
Upstream pond volume event end value range (m^3)		322 - 4023
Downstream pond volume event end value range (m^3)		43 - 3061
Max recorded pond storage (m^3) (% full)	Upstream Pond	4262 (100%)
	Downstream Pond	3133 (100%)
Min recorded pond storage (m^3) (% full)	Upstream Pond	337 (8.4%)
	Downstream Pond	43 (14.7%)

Table 5.3. Key study site event characteristics for Wellhams. Events are analysed using pond volume data (indicated as m^3 or % full), where values and ranges presented are extracted based on the full pool of events.

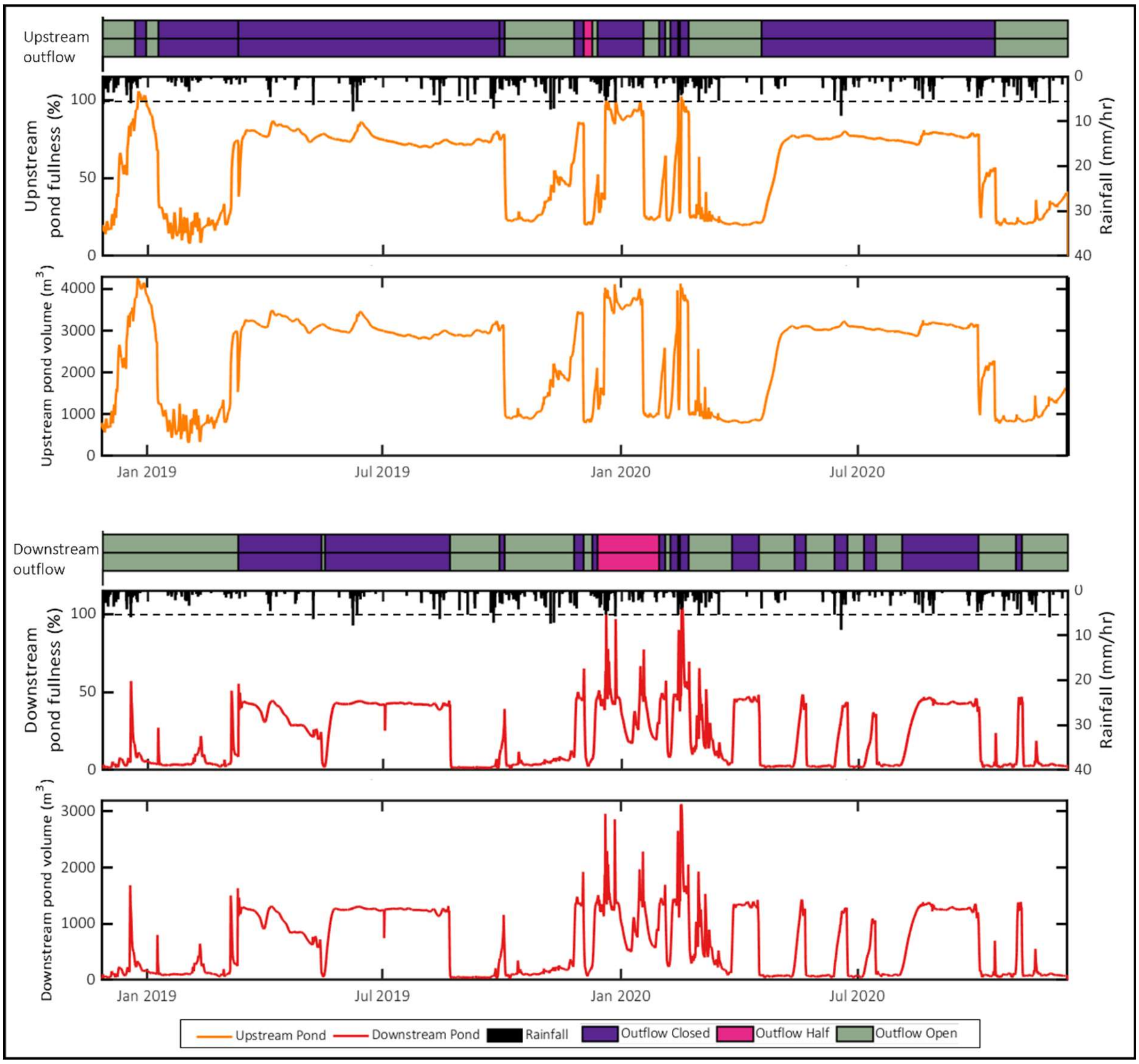

Figure 5.4. Full time series for Wellhams, the monitored period presented is from November 2018 – December 2020. Detailed is separate pond percentage fullness, storage pond volume and associated outflow management (kept open, half or closed for each individual pond). Dotted black line on both upstream and downstream pond storage percentage capacity plots illustrate 100% capacity reached, which is exceeded on 5 occasions for the upstream pond and 3 occasions across 2 events for the downstream pond.

5.4.2. What are the impacts of pond structure and design for pond storage?

This section details the impacts of online pond design and structure for its overall function (its ability to store water during rainfall events) across the time series and the separated rainfall events. The key components of pond structure at Wellhams are the overall capacity (potential storage, based on the excavation of the main-channel) and the outflow mechanisms at the outlet of both ponds.

At Wellhams, storage occurs when pond inflow exceeds pond outflow. During rainfall events and particularly when the outflows are closed, pond levels can rise above the overflow pipe, with volumes up to 2850m^3 (70.6% of total pond capacity) before spilling (through the overflow pipe). When the upstream pond outflow is open, volumes up to 660m^3 (16.4% of total capacity) can occur before any spilling through the main sluice gate. Downstream pond filling occurs from upstream pond outflow: when upstream volumes are >660m^3 (open outflow) or >2850m^3 (closed outflow). Downstream pond spilling occurs when volumes are >45m^3 (1.5% of storage capacity) when outflows are open and water spills through the main sluice. When outflows are closed, spillage occurs when volumes are >1300m^3 (43.9% of storage capacity) through an overflow pipe. Table 5.4 summarises these structural controls.

These storage controls based on the pond structure are reflected in Figure 5.4, where outside of event periods or when the outflow sluices have been opened or closed within the past 72 hours, constant pond volumes are maintained due to a steady small inflow from upstream springs. Across all events, open and closed outflow events present markedly different impacts for pond storage capabilities. Figure 5.5 illustrates the impact of pond outflow mechanisms (positioned open - closed) on event pond volume rise and peak. Lower peak volume values are typically extracted from open outflow events, with a large range of volume rises for both ponds. Higher peak volume values are typically extracted from closed outflow events. Indeed, peak volumes are a maximum of 4129m^3 for the upstream pond and 3118m^3 for the downstream pond for closed events, compared to 2665m^3 for upstream pond and 1931m^3 for downstream pond for open outflow events. These peaks are accompanied with a full range of pond rise values (for example, up to 2214m^3 for closed upstream events). For the upstream pond (Figure 5.5a), the majority of closed outflow events produce higher peak volumes than any open outflow event (35/38 plotted here). The three closed outflow events with lower peaks also present among the lowest rainfall depths (max 6.8mm). There are also few open outflow events that produce upstream pond peaks higher than a closed outflow event (6/26 events). This is also apparent for the downstream pond (Figure 5.5b), where 9/38 closed outflow events produced higher peak volumes than a open outflow event. Indeed, only 5/26 open outflow events produced higher downstream pond peaks than a closed outflow event.

<table>
<tr><th></th><th>Upstream pond</th><th>Downstream pond</th></tr>
<tr><td>Pond filling (open upstream outflow)</td><td rowspan="2">Constant (upstream springs)</td><td>Upstream pond >660m³</td></tr>
<tr><td>Pond filling (closed upstream outflow)</td><td>Upstream pond >2850m³</td></tr>
<tr><td>Open outflow pond spill (main sluice)</td><td>>660m³ (16.4%)</td><td>>45m³ (1.5%)</td></tr>
<tr><td>Closed outflow pond spill (overflow)</td><td>>2850m³ (70.6%)</td><td>>1300m³ (43.9%)</td></tr>
</table>

Table 5.4. Structural controls on storage. Pond filling refers to the upstream conditions for inflow. Pond spill refers to minimum pond volumes before outflow occurs through main sluice or overflow pipe. Values are volume (m^3) and pond percentage fullness (%).

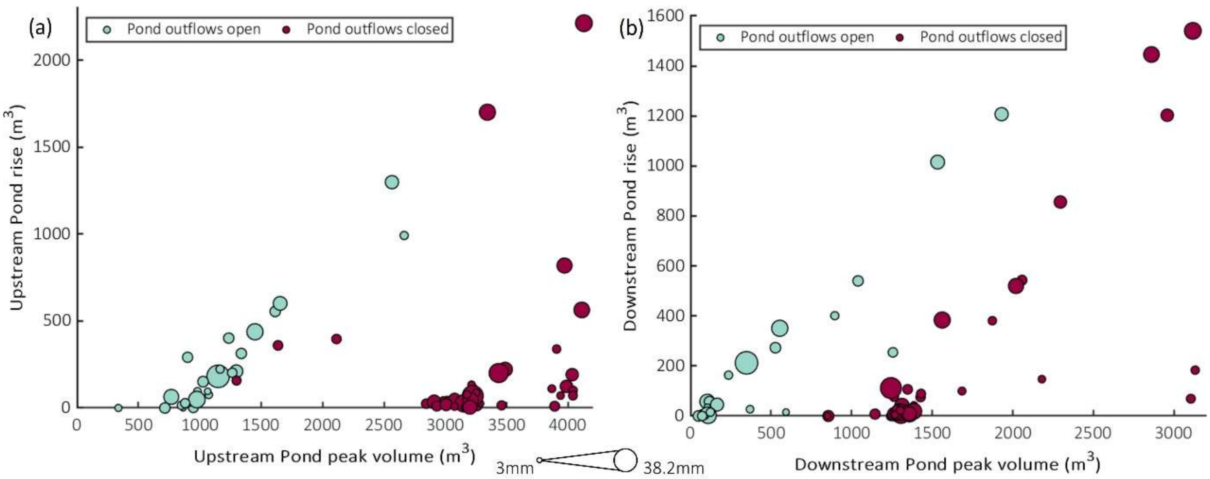

Figure 5.5. Impact of structural controls on event pond volume rise and peak for upstream (a) and downstream (b) pond at Wellhams. Size of the scatter is proportional to event rainfall depth (mm).

5.4.3. What are the hydrological controls on online storage ponds?

We now consider the impacts of key hydrological inputs for pond function (its ability to store water during rainfall events) across the time series and the separated rainfall events. The hydrological inputs are examined according to event rainfall and antecedent conditions (API value). To importantly follow on from the presented results for the events captured and structural controls (section 5.4.2), open and closed outflow events are presented separately.

The impact of event rainfall depth (mm) and antecedent conditions (API) for pond volume peak is illustrated by Figure 5.6, where open and closed outflow events are separately presented. Small correlations can be drawn from API and pond peak volume (r value of up to 0.69, with a r^2 value of 0.47, see Figure 5.6b), based on Pearson's correlation coefficient. There is marked variation for where event rainfall is plotted against pond volume peak, with no correlations drawn (see Figure 5.6c and d). Where pond volumes are high prior to an event (eg. closed outflows), the resultant pond peaks may be high regardless of the event rainfall or API, which is reflected in a low pond rise. Thus, it is suggested that pond structure (outflow opening and closure) may have a far greater impact on storage volume peaks than event hydrological inputs (here analysed as event rainfall and API).

The seasonal distribution of open and closed outflow events are illustrated by Figure 5.7. Firstly, outside of the December-March period, no events with a volume rise >580m^3 occurred for the upstream pond or >545m^3 for the downstream pond. This compares to a highest pond volume rise of 2200m^3 for the upstream pond and 1540m^3 for the downstream pond. Thus, by a marked proportion, the largest pond filling events occurred in the winter, despite the occurrence of some high event rainfall depths during June in 2019 and 2020 (up to 33mm, compared to a maximum recorded event rainfall depth of 38mm).

Figure 5.7 also illustrates the relationship between each pond volume rise and event peak. As pond volume data is presented here, where high pre-event storage can feasibly occur as a result of outflow closure, high peak volumes can realistically occur throughout the year and regardless of the event inputs (eg. rainfall). This is reflected on Figure 5.7 where certain events with very high downstream pond peaks (>3000m^3) also present very low upstream pond volume rises (<80m^3). Equally, if pre-event storage volumes are very low (eg. due to an open outflow, or where outflows have only very recently been closed), a very high pond volume rise will be required to produce a pond peak that even equals that of events with high pre-event volumes.

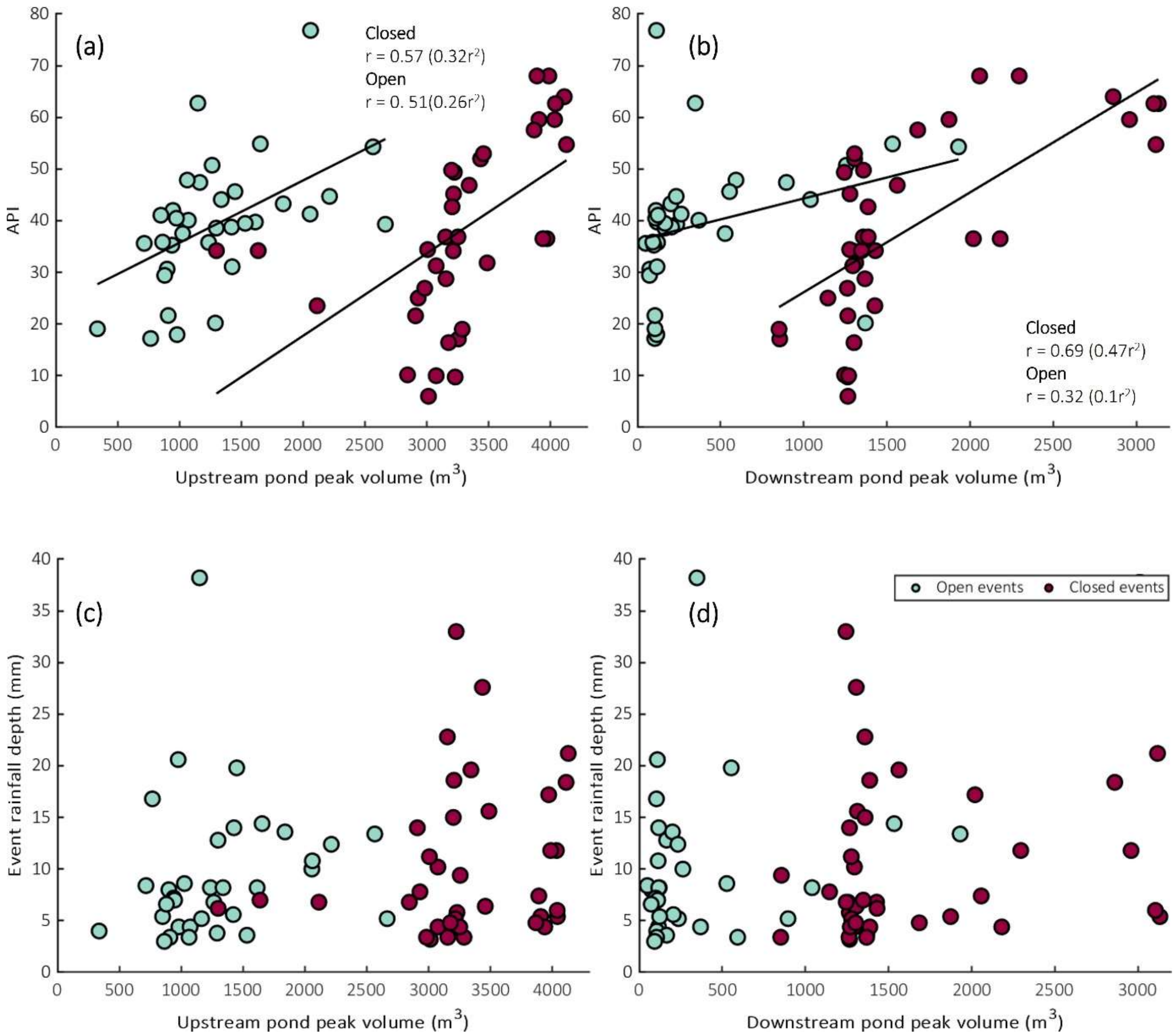

Figure 5.6. Impact of API and event rainfall on upstream and downstream pond peak volume for all extracted events. Events with closed and events with open outflows are separated and correlations are drawn for (a) and (b) between API and upstream and downstream pond peak volume, based on Pearson's correlation coefficient.

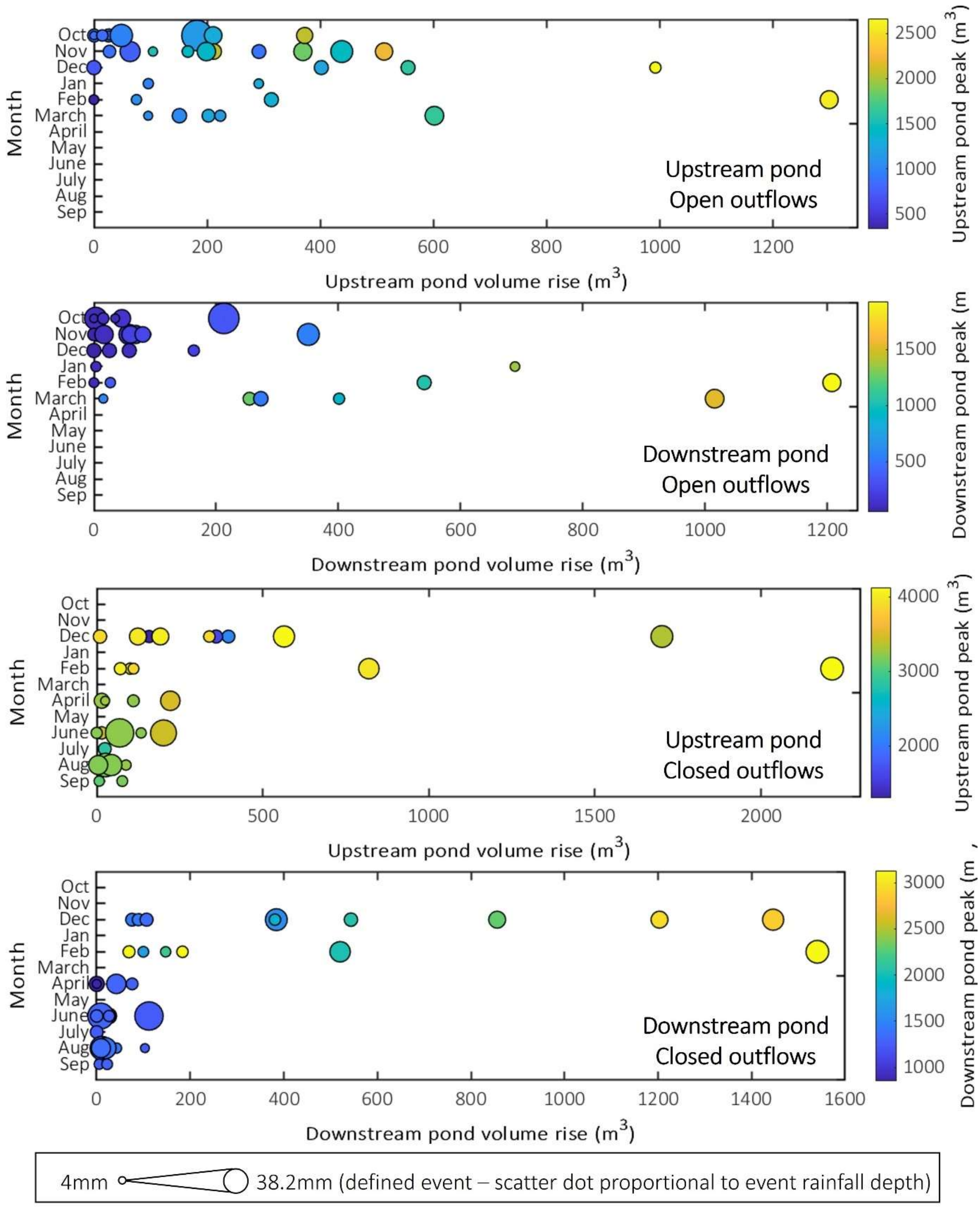

Figure 5.7. Impact of seasonality (month) and event rainfall depth on event pond volume peak (colourbar). Each scatter dot represents 1 analysed event that is plotted according to its month, flow rise and peak pond volume height.

5.4.4. What is the role and impact of outflow management for online storage ponds for Natural Flood Management?

The role and impact of outflow management of the Wellhams online water storage ponds is assessed in line with the five tasks and success criteria introduced in section 5.3.5 (Table 5.2). The level of success for each task for the applicable events is used to highlight the appropriateness (is the task useful and effective for ensuring that ponds work as well as they can) and feasibility (even if the task is useful, is it actually workable for the flood wardens to complete) of each task for the management of pond function at Wellhams.

Task 1. Maintain a low pond storage prior to large rainfall events

In total, 32 rainfall events were deemed applicable for task 1, based on the event having a total rainfall depth of >10mm (above the mean event rainfall depth) and occurring between October and March. Of these 32 events, 23 were found to have a total site storage of <50% total capacity (3694m^3) at the event start (see Figure 5.8a). For winter events (December-February), pre-event storage capacities of up to 94% and 49% were recorded for the upstream and downstream pond, respectively. However, of the 9 events that presented a total site storage of >50% total capacity (3694m^3), all of these occurred within 48 hours of another large rainfall event (one of the 32 rainfall events separated for this task). This meant that achieving low pond storage would have been infeasible within the short time period. No applicable events were found to result in this task being unworkable or not completed for the large winter events. This shows that overall, this task is appropriate and feasible for the management of pond function at this site.

Task 2. Close outflows prior to large rainfall events

In total, 32 rainfall events were deemed applicable for task 2, based on the event having a total rainfall depth of >10mm (above the mean event rainfall depth) and occurring between October and March when pond outflows are typically kept open. Of these 32 events, 10 were found to have both pond outflows closed at the event start (see Figure 5.8b). Furthermore, 5 events had the downstream pond closed and the upstream pond open or half-open. The remaining 17 events had open downstream pond outflows. This shows that for more than half of applicable events, outflows were either not able to be closed or it was not deemed necessary at the time to close them. This highlights that this task may be both less appropriate for the management of pond function. Moreover, pond closure prior to large rainfall events is not feasible on a regular occurrence as this task assumes that within the winter period, site visits may be possible multiple times during a week.

Task 3. Open outflows after large rainfall events

In total, 32 rainfall events were deemed applicable for task 3, based on the event having a total rainfall depth of >10mm (above the mean event rainfall depth) and occurring between October and March when pond outflows are typically kept open. Of these 32 events, 14 were found to have both pond outflows open within 48 hours of the event end (see Figure 5.8c). Of the 18 events where outflows were not opened within 48 hours of the large rainfall event, 9 had the downstream pond half-open and the upstream pond open or half-open within 48 hours of the event end. Within 48 hours of the remaining 5 separated events specific to this task, another large rainfall event occurred (one of the 32 rainfall events). No applicable events were found to result in this task being unworkable or not completed for the large winter events. However, it is important to note that for more than half of the applicable events, opening outflows after large rainfall events was not feasible and thus working around this, by keeping outflows half open or by keeping them closed where another large event was forecasted soon after a first one was essential. Thus, this task should be viewed as needing adjustability and flexibility for the management of pond function at this site.

Task 4. Maintain a high pond storage during low rainfall periods

In total, 14 rainfall events were deemed applicable for task 4, based on their low API value (<22), above average event rainfall total (>10mm) and occurrence between April and September (when ponds are routinely closed to maintain high storage for summer months and wider NFM benefits). Figure 5.8d highlights that for 12 out of these 14 events, high pond storages were maintained during low rainfall periods. For the other 2 events, an identified blockage at the downstream pond outflow meant that the mechanisms could not be closed correctly and as a result outflows were kept open until the material could be removed. These 2 events were deemed as a 'adjustable success' because external reasons were present for the lack of pond closure. The execution of task 4 shows that for the majority of events, maintaining a high pond storage across the summer months was feasible and appropriate for pond management. There were no events reported where a low pond storage was maintained during low rainfall periods with the exception of where this was necessary and thus the execution of this task can be deemed to be largely feasible and applicable for ensuring pond function, but specifically for the wider benefits of NFM.

Task 5. Secure maintenance on the ponds where required

Of the 94 events separated, 9 of these were found to coincide with 3 separate instances of faults across both ponds (see Figure 5.8e). In December 2018, the upstream pond outflow was blocked, preventing draining. In May 2019, the downstream pond outflow was blocked, forcing the mechanism open. During February 2020, following a series of large rainfall events, the downstream pond was left with highly unstable banks and a risk of collapse following pond capacity exceedance. All 3 of these instances were resolved and repairs conducted by contractors within a month of identification by the flood wardens. Amendments were made to both ponds in July 2020 by adding additional 300mm overflow pipes, positioned at a higher level than the original overflow (see Figure 5.9). Of the 9 events which occurred whilst pond faults were present, 5 events resulted in additional negative local impacts, primarily local flooding due to pond overtopping (see Figure 5.8f). Across the monitoring period, pond capacity was exceeded (where water flowed onto surrounding farmland) on 5 occasions for the upstream pond and 3 occasions for the downstream pond. Thus, a small but marked quantity of events occurred whilst pond faults were present at the site. However, more importantly, over half of these events resulted in additional negative impacts (most commonly, farmland flooding). This task highlighted the importance of the fast response and identification of issues at the site by the flood warden team and emphasises that passive management of this site would not be appropriate and would markedly impede pond function.

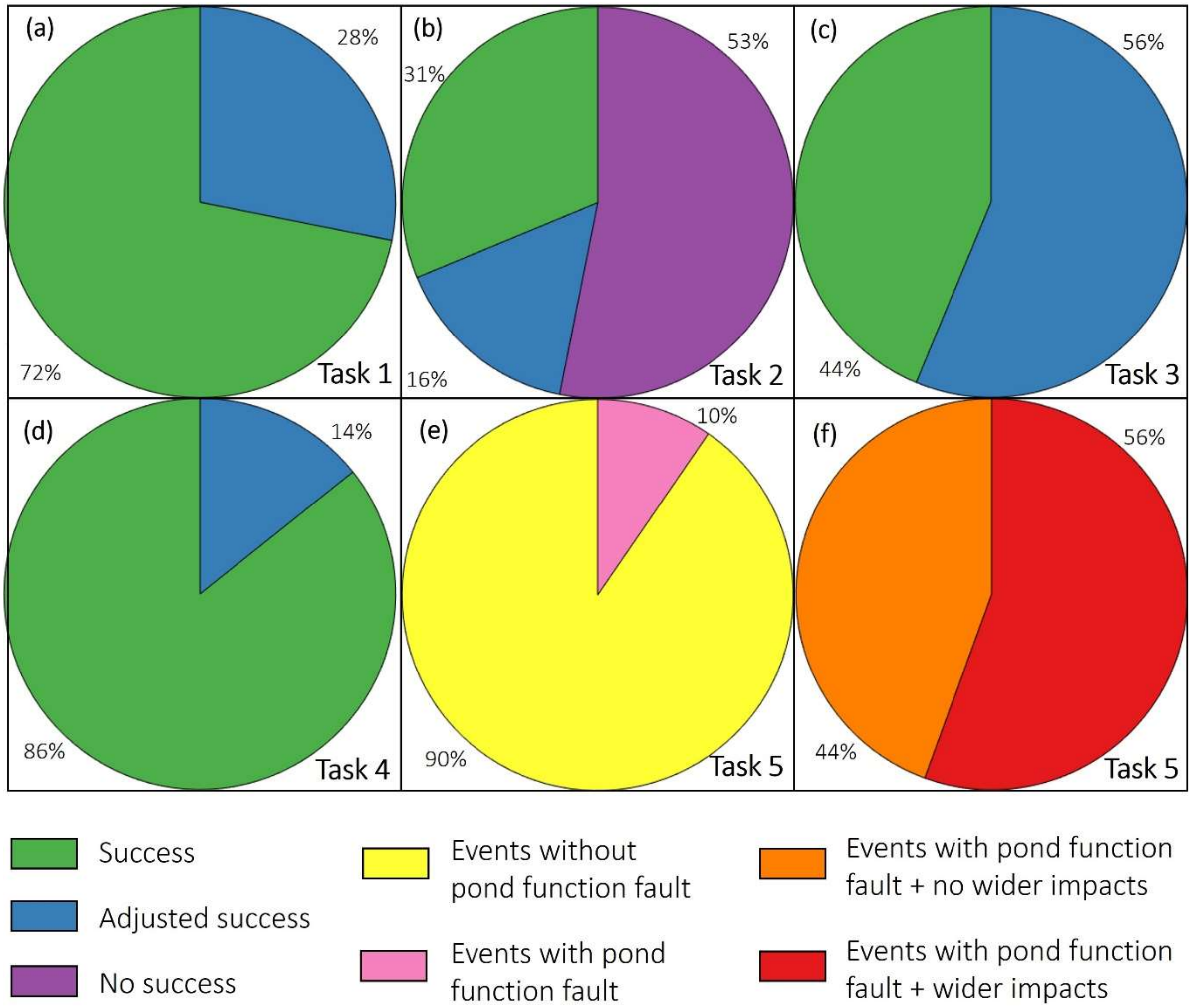

Figure 5.8 Summary of the success of the key tasks undertaken to manage online storage pond efficacy across the monitoring period. Plotted are task 1 (a), task 2 (b), task 3 (c), task 4 (d) and task 5 (e and f). Success is categorised according to 'success', 'adjusted success' and 'no success for task 1 (a), task 2 (b), task 3 (c), task 4 (d). For task 5, success is categorised according to firstly, the proportion of events with and without function faults (e) and of those events, the proportion of those where faults result in local issues or not (f).

Figure 5.9. Maintenance examples in July 2020. Images show reinforcement of downstream pond outflow sluice, with wooden poles, bank reinforcement and coir matting (a). Also, the construction of an additional (higher) downstream pond overflow pipe (b).

5.4.5. What is the impact of online storage ponds on pond volume metrics?

Using monitored pond data, temporal metrics were extracted from all events, highlighting the time to the start of pond response (Figure 5.10) and upstream to downstream pond peak travel time (Figure 5.11). Figure 5.12 illustrates the largest magnitude rainfall event as an example.

The speed of pond response varies markedly between events (Figure 5.10). For the upstream pond, the response time is 1.1 hours for events where both outflows are open, compared to 1.6 hours for events where both outflows are closed. For the downstream pond, the pond response time is faster during open outflow events (1.2 hours median value), compared to closed outflow events (1.4 hours median value). This also shows higher median pond response times for the downstream than upstream pond. There are some marked exceptions to this, including the highest recorded API event that presents a pond response time of 24.7 hours for the upstream pond, with a delay to 25.9 hours for the downstream pond. This elongated pond response time is attributed to a very long period of low intensity rainfall (peak rainfall occurred 32 hours after event start). Thus, pond filling is high, but very gradual and as a result the lag for downstream pond volume to reach the 5th percentile is 25.9 hours.

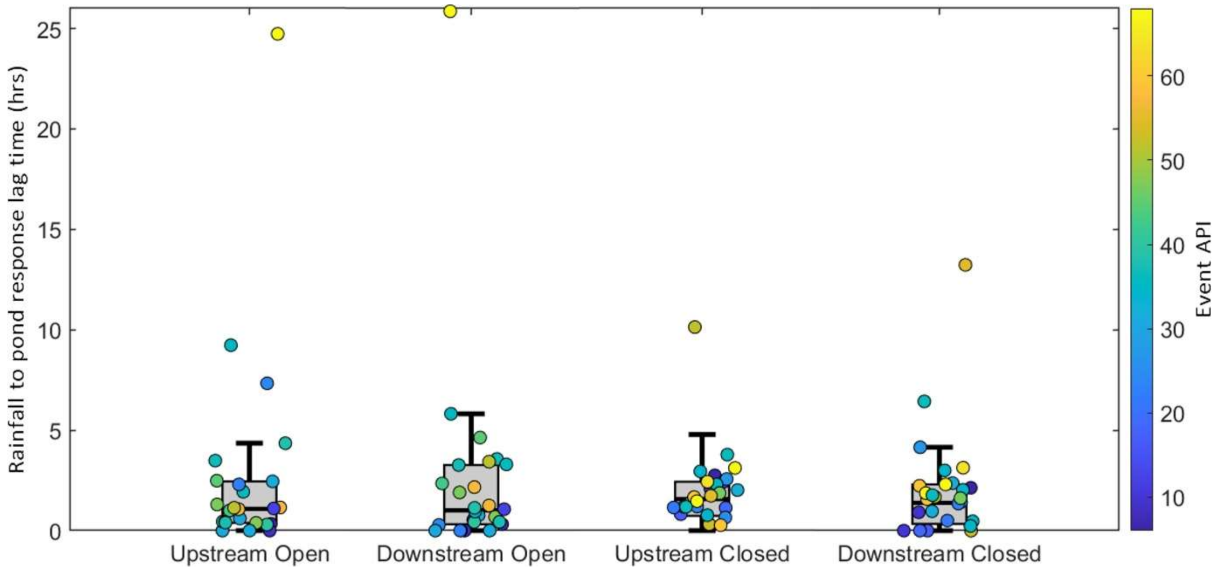

Figure 5.10. Lag time between the start of rainfall (event start) to the start of pond response (5th percentile of pond volume rise). Upstream and downstream pond responses are presented, for closed and open outflow events. Event API is illustrated by the colourbar.

Pond volume peak travel times varied markedly between events (Figure 5.11), recorded up to 27.3 hours and down to -32.6 hours. Both closed and open event plots presented median values of 0. Events with higher pond volume rises present positive peak travel times (colourbar, Figure 5.11), where events with negative travel times show a maximum downstream pond rise of 383m^3 (out of a maximum rise of 1541m^3). These peak travel times highlight the complexity of online pond filling and spilling. If system inflow and outflow were used to gain peak travel time (see section 5.3.3 for rationale), a linear system (positive peak travel times) would be expected.

Finally, Figure 5.12 illustrates a large rainfall event for Wellhams: the 29th, February 2020, causing high pond filling and volume change. This was an event where both outflows were open, resulting in low storage volumes at the start of the event (27.7% for upstream pond and 20% for downstream pond). Upstream to downstream pond peak travel time is 5:10hrs, with downstream pond volume reaching its peak 10hrs after the extracted rainfall peak time.

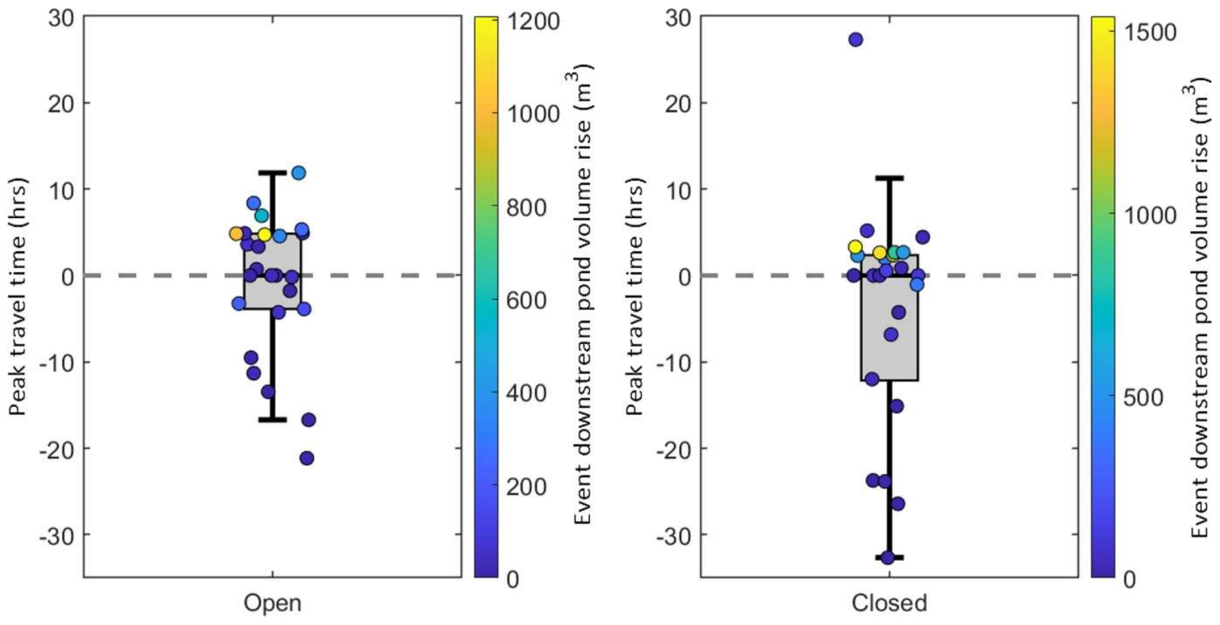

Figure 5.11. Peak travel time between the upstream and downstream pond, compared closed and open outflow events. Event API is indicated by the colourbar. A peak travel time above the 0 bar indicates downstream pond to peak after the upstream pond.

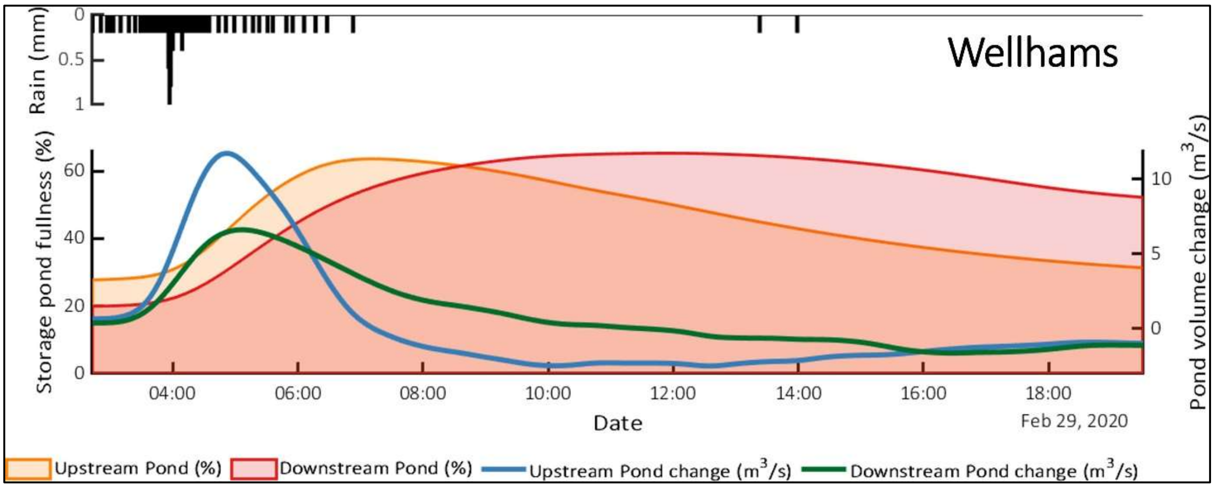

Figure 5.12. Presented is a large magnitude recorded event for Wellhams: 29th of February 2020, where storage pond fullness, pond volume change and rainfall are depicted.

5.5. Discussion

5.5.1. Online storage ponds require regular maintenance and close management to sustain their storage function

The first section of analysis of this chapter analysed the role and impact of outflow management at Wellhams according to five, key tasks that are carried out at the site by the flood warden team to sustain pond function: principally its ability to effectively store water and slow the flow. Two key factors were examined to determine the success of these tasks for the events analysed. Firstly, the appropriateness and impact of each task for sustaining pond function, to highlight whether the task was useful for enabling the ponds to store water as effectively as possible for slowing the flow. Secondly, to highlight the feasibility of each task, for instance, which is equally important to consider because regardless of the potential impacts or benefits of management, it has to be viable for CFGs to carry out in order to be successful (Short *et al.*, 2019). This aims to respond to key research gaps in the NFM literature, where there is currently a limited quantity of evidence for how NFM features should be managed, and the frequency and types of maintenance that may be required. This information is important to inform practitioners on the performance and design life of NFM features and reduce current NFM uptake barriers which include a lack of surety of management plans for constructed NFM feature (Ngai *et al.*, 2017; Wells *et al.*, 2020).

Overall, it was found that outflow management was successful at Wellhams, although the deemed success and execution of the five key tasks varied. For tasks 1 and 3, which focussed on having a low pond storage prior to events, and open outflows after events, respectively, the majority of events were deemed a ‘success’ or ‘adjusted success’. These tasks were deemed key to ensuring that there were large pond storage capacities for large winter events. The flexibility and adjustability of these tasks was very apparent as on a number of occasions it was not possible to complete these tasks where multiple consecutive events occurred in a short period. Indeed, for more than half of the applicable events, task 2 was deemed a ‘no success’ as it was not feasible to close outflows prior to every large winter rainfall event. Thus, it is important to note that for CFG management plans, a great deal of flexibility may be required to manage large winter events. For instance, on the one hand, it may be deemed ‘ideal’ to have low volumes at the event start (task 1), produce large storage filling (task 2) and subsequently drain ponds following events (task 3). However, the documentation of management of winter events at Wellhams has highlighted that this may not be feasible in terms of the human time required for site visits and there being not enough time between large events for the pond system to progress through all three steps.

Maintaining a high pond storage during low rainfall periods (task 4) was overall deemed very successful and feasible at Wellhams. The summer period also proved an ideal time to conduct any needed maintenance works on account of fewer expected rainfall events. In these instances, the pond volumes could be forced low temporarily though outflow opening and closure. Although not coinciding with any events, it was apparent from time series visual analysis, that on 3 separate occasions during summer 2021, unidentified persons were found to have forced open the downstream pond outflow sluice, resulting in pond drainage. During the summer month, fewer visits were required to the site and as a result these alterations were not discovered for a period of weeks each time. Although this did not result in any marked negative consequences, a padlock was added to the downstream sluice as a future deterrent. No official assessments were made of the wider benefits of maintaining high pond volumes during summer, however swan populations and nest sites were identified at the ponds in both 2019 and 2020 (see Figure 5.3).

The fifth examined task conducted by the flood warden team was arguably presented as the most important for ensuring both site longevity and pond function. Maintenance was required on 5 separate occasions across the monitoring period, where 9 events occurred whilst pond faults were present. Of these 9 events, 5 of them resulted in local farmland flooding due to pond capacities being exceeded. This occurred in the upstream pond in December 2018, where an outflow blockage prevented a large amount draining and as a result pond overtopping onto the surrounding farmland. This was fixed by contractors in January 2019, allowing the upstream pond to be drained. In addition, a plastic piece jammed the sluice gate open in May 2019, meaning the downstream pond could not be closed, as per typical summer management (to maintain a high storage for wildlife, when few large storms were anticipated). Upon investigation, this was removed by contractors. In addition, the winter events of February 2020 resulted in considerable bank instability and a high risk of bank collapse at the downstream pond due to high volumes of water and pond capacity being exceeded. As a result, additional earth reinforcement took place at the downstream pond outflow, along with the installation of wooden poles and coir matting. In addition, additional

300mm overflow pipes were added to each storage pond, positioned at a higher level than the original overflow. Constructed in July 2020, volumes did not reach these additional overflow levels before monitoring finished in December 2020. This was anticipated as these additional overflow pipes were installed to only operate when storage capacity was very high, with volumes that have only been recorded during the largest rainfall events (eg. February 2020 events). As these measures were largely preventative for future larger events and to avoid bank collapse, no direct impacts on the monitoring data were shown. In the future, it is anticipated that the ponds will be able to cope with higher volumes and inflows, without overspilling. The examination of these maintenance requirements confirms current citied barriers to NFM uptake, which include concerns over local flooding as a result of a lack of maintenance (Wells *et al.*, 2020).

Wellhams pond management has highlighted the importance and benefits of community engagement and catchment flood groups to facilitate NFM measures to function as optimally as possible. Essential to pond function is adequate storage capacity for rainfall events, which requires sufficient spilling (Dadson *et al.*, 2017), which in the case of this site was often dependent on careful outflow management. If a combination of insufficient outflow and high pre-event storage volumes occur, pond capacity can be exceeded, resulting in local farmland flooding, as occurred at Wellhams. However, a flexible approach to maintenance and site improvements, whereby additional outflows were added and repaired, meant that ponds could continue to function as designed. The importance of CFGs and similar organisations, in line with a 'bottom up' approach to NFM has been highlighted elsewhere (eg. Howgate and Kenyon, 2009; Mehring *et al.*, 2018; Old *et al.*, 2018; Short *et al.*, 2019; Newson *et al.*, 2021). However, it is important to note that the success of community engagement for NFM is not shared ubiquitously. Newson *et al.*, (2021) highlights survey results by the Catchment Based Approach/National Flood Forum (2020) which to an extent discredited the role of CFGs for catchment-based management.

This approach and the early results of a bottom-up approach to management and maintenance have been documented elsewhere, for example Old *et al.*, (2018) where a pilot scheme in Evenlode (UK) anticipated minimal maintenance, that can be conducted within existing agricultural practices. This chapter highlights that more complex NFM sites (eg. that have large storage potentials and control mechanism) require close management and thus the maintenance responses reported here are unlikely to be unique to Wellhams and should be factored in for other NFM site management plans.

The importance and impact of NFM maintenance or structural adjustment has been shown elsewhere in the literature, for offline storage ponds in the Belford catchment (Wilkinson *et al.*, 2010). Here pond drainage rate was increased (to 5-6 hours down from 24 hours) through increasing barrier gaps (Nicholson *et al.*, 2012). These modifications occurred under a similar rationale to Wellhams, where additional overflow outflow pipes were added at both ponds, as at both sites outflow rate was not sufficient during high magnitude events. A key contrast is that at Belford ponds, full drainage was required so that the land could be used by the landowner outside of flooded periods (Wilkinson *et al.*, 2010b), whilst at Wellhams, ponds are in-channel and so a constant flow and storage is anticipated. Further maintenance considerations for NFM structures documented elsewhere include sediment removal to ensure overall storage capacity is preserved (Evrard *et al.*, 2008b; Barber and Quinn, 2012; Wilkinson *et al.*, 2019). However, to date, pond silting has not posed a marked issue for Wellhams.

5.5.2. Outflow management of online ponds has a greater impact on slowing system travel time and reducing magnitude

The second section of analysis of this chapter considered the impact of rainfall events for pond storage and slowing the flow at Wellhams, according to two key hydrological metrics and the presentation of a large magnitude event in detail. As highlighted previously, a key limitation of this chapter is that the impact of NFM structures on outflows (relative to inflows) was not possible, which is a key contrast to analysis of NFM storage elsewhere (eg. Thomas and Nisbet, 2007; Evrard *et al.*, 2008; Nisbet *et al.*, 2015; Puttock *et al.*, 2017, 2021). As an alternative, the impact of rainfall events on pond storage timing metrics was examined, where pond volume increase was used as a direct indicator of flow that has not directly transformed to outflow. Equally, where pond volume decreases, there is greater outflow than inflow; thus, indicating overall system spilling. Understanding the timings and metrics associated with these processes provide useful indicators of the system complexity, the impacts of outflow management (specifically open versus closed events) and system storage capabilities. This aims to respond to current NFM literature gaps to present empirical evidence for the impact of online water storage ponds within NFM schemes, based on their response to rainfall events and potential ability to slow the flow. This information is important to inform and advise NFM practitioners on the potential uses of storage features that currently fall on the boundary between more traditional/hard engineering flood management and those that work with natural processes.

Pond storage at the site is largely an outcome of there being outflow sluices at each pond, which alter the natural inflow-outflow equilibrium produced by upstream springs at Wellhams which provide a regular inflow that is matched by a regular outflow, behaving not dissimilarly to natural open lakes (eg. see Wang *et al.*, 2020). Indeed, pond volume is near constant outside of periods when outflows have been recently opened or closed or where there is a rainfall event. During rainfall events or immediately following outflow closure, greater inflow than outflow occurs, producing site attenuation, reflected through pond volume increases in the event datasets.

These increases in pond volumes in response to rainfall events are firstly reflected through a high variability in results, showing the nonlinearity of the upstream to downstream pond system. For example, in a number of cases, downstream pond response occurred before the upstream pond (Figure 5.10) and both positive and negative upstream to downstream pond travel times were extracted (Figure 5.11). This nonlinearity can be attributed to varying pre-event storage volumes in both ponds, the effects of outflow closure and the fact that the two ponds have different total storage capacities. Therefore, it is feasible for the downstream pond to reach peak volume before the upstream pond as it has a lower total capacity to reach before overspill occurs. Indeed, in the case where a positive peak travel time is extracted, this may be highly indicative of system attenuation as this demonstrates that despite the larger quantity of storage to fill before overspilling, the upstream pond still reaches its peak faster than the downstream pond. Indeed, positive peak travel times were extracted from events with higher downstream pond rises (Figure 10). This is likely due to the longer amount of time for pond volume to reach the peak, relative to low rise events. For events with large rainfall totals, a large pond volume rise is indicative of effective pond functioning as the potential storage capacity is being used to full effect and large volumes are being temporarily stored.

Pond response to Storm Dennis (14th-17th of February 2020) demonstrates an example of this. Outflows were closed 13 hours prior to the event start, ensuring a high storage capacity for start of rainfall and a high fill potential. Indeed, when closed (10am), ponds were 27% and 37% full for the upstream and downstream pond respectively, and by the event start (11pm), pond storages were 40% and 47% full for the upstream and downstream pond. By 2.45pm (upstream pond) and 5pm (downstream pond) on the 15th of February, pond capacities had been exceeded (>100%), where >38mm of rainfall occurred at Wellhams by 9am on the 21st of February, when both outflows were opened. The time taken for ponds to reach their peak volume (and in the case of this event, exceed capacity) was 2.25 hours longer for the downstream pond. If no in-channel ponds existed at this site, system peak flow travel time would be expected to be small due to the short distance (250m). Although these metrics are extracted using pond volume data, this may still be indicative of a peak delay downstream, on account of substantial pond filling from both ponds. In the future, pond capacity may not be exceeded on account of the construction of additional, higher overflow pipes. Indeed, these represent a careful balance between achieving as much temporary water storage during events as possible, whilst not causing additional localised flooding across farmland. On account of the large areas and complexities of calculating site-wide storage based on the drone DEM, determining pond storage volumes when they exceed 100% is complex and therefore all values >100% on the produced time series are expected to be inaccurate and larger in reality.

5.5.3. Recommendations for future online water storage pond management and maintenance

Based on the monitoring and results of this chapter, a series of key recommendations for future management of similar NFM sites can be made.

Firstly, close management, for example as with a flood warden team at Wellhams is recommended, on account of the expected maintenance and outflow management required for NFM structures that involve additional engineering. This requires regular (monthly) visits in addition to visits prior to and following large, forecasted rainfall events. If this level of continuity is not possible (eg. due to limited local engagement or lack of funding), then outflow mechanisms may not be suitable due to the risk of blockage. Whilst closed outflows potentially present higher levels of attenuation, having a constant, high storage volume in-channel (as is the case at this site when outflows are closed), increases additional hazards, such as pond overspilling.

There is a strong chance that maintenance will be required at other sites, given the multiple separate occasions where it was needed at Wellhams, particularly following large rainfall events. This should be deemed highly important to respond to as site despair may result in local negative impacts, such as farmland flooding if pond capacities are reached. In certain instances that may have further negative consequences for the impression that these features give locally, and could limit future NFM uptake (Wells *et al.*, 2020), for instance if they are perceived to results in local flooding issues. This presents a key contrast to other NFM features, where inattention to maintenance is unlikely to result in introduced negative implications, for example the silting up of in-field runoff attenuation features, which could mean they no longer function for sediment and temporary runoff capture (Wilkinson *et al.*, 2019).

Maintaining high pond volumes when large rainfall events are not anticipated has been deemed highly feasible at Wellhams, where outflows can be kept closed between April and September. It is important to maintain regular site visits when storing these larger flows, to check on the state of the outflows. In addition, these summer months present practical times to conduct maintenance works.

5.6. Conclusions

This chapter has examined the role and impact of online water storage ponds for slowing the flow, based on an assessment of site management conducted to maintain storage pond functioning, and also an analysis of pond responses to rainfall events. In addition, a list of key recommendations for management and maintenance requirements for online storage pond NFM sites are detailed.

The analysis of key inputs present at Wellhams has shown that the pond structure, particularly where outflows can be opened or closed is likely to have a far more marked impact on storage capabilities than the impacts of rainfall events. Overall, pond volume responses to rainfall are highly variable, but for the largest recorded events, where substantial pond filling occurs (low pre-event volumes), marked upstream to downstream pond travel times can be extracted. In future monitoring projects, channel monitoring immediately upstream and downstream of systems may reveal the direct impacts of ponds on downstream flow. However, as revealed during monitoring of Wellhams, uncalculatable quantities of water are lost (assumingly from throughflow) at the site, which may make balancing inflow and outflow quantities complex.

Substantial pond management occurred throughout the monitoring period, where a series of identified tasks, including maintaining low volumes before large, forecasted rainfall events, were deemed appropriate for maintaining pond function. However, it was stressed that a high level of flexibility is required when managing this and similar sites, for instance where a balance must be struck between what is feasible to be conducted by a community flood group and what impacts are being aimed for. The role of the flood warden team at Wellhams has been essential for managing and maintaining the ponds to not only respond to issues and introduced negative impacts, such as local flooding as a result of pond faults, but also to aim to maximise wider NFM benefits and the function of the ponds to store floodwater.

6. Subsoiling as an agricultural management method for Natural Flood Management

6.1. Context

Research question 4: How effective is subsoiling as a soil management method for Natural Flood Management?

The use of subsoiling as an agricultural management method on farms is widely accepted to reduce local soil compaction issues (eg. Evans *et al.*, 1996; Schwartz and Smith, 2016; Xue *et al.*, 2019; Zhang *et al.*, 2020; Lou *et al.*, 2021). However, how reductions to local compaction may extend to wider flood risk reduction is far more uncertain. This uncertainty arises because there are many on-site factors affected by subsoiling (eg. soil compaction, infiltration rate, aggregate size etc.) that impact runoff generation and flow pathways with implications for contributions and timings to in-channel flows. Empirical datasets that examine the impact of agricultural management methods, can provide useful insights into the linkages between on-site management strategies (field) and in-channel impacts (flows and flood risk). These will help improve hydrological model parameterisation and reduce a reliance on using singular values to characterise soil properties at a field or even catchment scale. This chapter assesses the impact of subsoiling as a machinery based agricultural management method for NFM, at five study sites in the Tone and Parrett catchment, Somerset where partial field trials have been conducted. This chapter aims to produce a series of soil hydrological datasets to assess the impact of subsoiling, on infiltration, overland flow generation, and suspended sediment yield at the plot scale. This is supplemented with a comparison between compaction (bulk density) and organic carbon values between subsoiled and controlled plots.

6.2. Introduction

Long-term intensive farming practices have resulted in extensive soil degradation in UK agricultural catchments since the mid-20th century (Wilkinson *et al.*, 2010a; Marshall *et al.*, 2014; Humphries and Brazier, 2018). These land use changes and landscape modifications, have had widespread implications for soil structure and health, notably soil compaction due to the concentrated use of heavy machinery and livestock (O'Connell *et al.*, 2004; Raper, 2005; Peralta *et al.*, 2021). Soil compaction is widely attributed to reducing soil pore sizes, and therefore inhibiting root-system penetrability, reducing infiltration, water and nutrient storage, and increasing overland flow (Lasanta *et al.*, 2000; Lou *et al.*, 2021). This ultimately affects soil health, as a key determinant of the ability of soil to provide ecosystem services such as plant and animal growth and productivity, water, and air quality and to function as a living system (Doran and Zeiss, 2000; Trivedi *et al.*, 2018).

In more recent years, there has been a growing recognition that conventional agricultural practices are increasing flood risk in the UK and worldwide (Holman *et al.*, 2003a; Franklin *et al.*, 2007; Evrard *et al.*, 2008b; Palmer and Smith, 2013). Farm practices that contribute to soil degradation, such as the use of chemicals and heavy machinery on farms have resulted in widespread depletion of soil nutrients and increasing soil loss through erosion and extensive soil compaction, including capping, where a hard crust is formed on the top layer of soil. For example, the creation of tramlines and farm tracks, produce concentrated areas of compaction, that have increased preferential runoff pathways on farms. In turn these produce enhanced overland flow because infiltration rates are reduced due to an increase in soil bulk density and associated decrease in macropore connectivity, pore sizes and porosity (Palmer and Smith, 2013; Alaoui *et al.*, 2018). These issues have been reported to affect 38% of agricultural sites surveyed from 2002-2011 in SW-England (Palmer and Smith, 2013) and 30-35 % of the Yorkshire Ouse and Uck, 20% of the Bourne and 40% of the Severn catchments (Holman *et al.*, 2003). In these studies, soil structural degradation and compaction is confidently attributed to producing faster, larger quantities of water into river courses, particularly during prolonged wet periods or high-magnitude rainfall events, and thus are seen as key indicators of flood risk increases due to intensive farming practices (Holman *et al.*, 2003b; Etana *et al.*, 2013).

To offset soil structure compaction issues, as well as wider soil degradation on farms, soil management methods, including conservation tillage, subsoiling, cover crop sowing and crop rotations, have been applied in agricultural catchments in the UK and internationally (O'Connell *et al.*, 2004; de Almeida *et al.*, 2018). These methods aim to improve soil physical, chemical and hydraulic properties for enhancing crop yields by increasing pore space and soil water holding capacity, thus enabling enhanced root growth and water and nutrient uptake for crop growth (Jin *et al.*, 2007). Subsoiling is a widely applied method within agriculture to reduce compaction by lifting and shattering compacted soil to loosen the subsoil and improve drainage, but without turning and disrupting topsoil structure (Burgess-Gamble *et al.*, 2018; Lou *et al.*, 2021).There is a considerable volume of literature regarding the use of subsoiling for improving soil physical properties, for example soil organic carbon (Zhang *et al.*, 2011; Tian *et al.*, 2014; Getahun *et al.*, 2018; Asenso *et al.*, 2019; He *et al.*, 2019a) and aggregate stability (Burgess *et al.*, 2000; Zhang *et al.*, 2011). In addition, by reducing compaction (Evans *et al.*, 1996; Burgess *et al.*, 2000; Feng *et al.*, 2018; Shukla *et al.*, 2020) and enhancing root growth (He *et al.*, 2019b; Xue *et al.*, 2019), subsoiling is attributed to improving crop yields (Jin *et al.*, 2007; Leskiw *et al.*, 2012; Asenso *et al.*, 2019; Yu *et al.*, 2019).

In recent years, soil management measures including subsoiling, have been placed under a new umbrella, with a focus on how these practices may reduce flood risk (O'Connell *et al.*, 2007; Deasy et al.,2014; Alaoui *et al.*, 2018). This is largely derived from how the potential benefits of soil management methods may extend to improving infiltration, drainage, saturated hydraulic conductivity and water storage capacity, as well as erosion (Sojka *et al.*, 1993; Feng *et al.*, 2018; Borek, 2020). For example, Smith, (2012) illustrated the potential of soil management to markedly reduce runoff peaks and increase soil water storage capacity when comparing aerated fields with those lightly compacted. This is based on the principles that improvements to soil structure will improve both local drainage issues, for example by increasing infiltration, as well as slow runoff: a reversal of the impacts of soil compaction (Lane, 2017). Laufer *et al.*, (2016) reported runoff reductions of 55% and 92% under reduced and strip tillage respectively, through high-magnitude rainfall simulations. Similarly, Rhoton, Shipitalo and Lindbo (2002) produced mean runoff values of 16.5mm for no-till treatments, compared to 27.8mm for conventional plots. These principles have also been applied to the regulation of low flows in UK, where scenarios of improved soil management practices demonstrated significantly higher low flow values in modelling applications by Smith (2012).

Soil management methods have also been shown to reduce soil erosion as a result of decreasing overland flow generation (Laufer *et al.*, 2016). This is important as studies have also demonstrated the implications of increased overland flow for generating amplified sediment transport downslope (Nolan *et al.*, 1997; Engel *et al.*, 2009; Laufer *et al.*, 2016). Indeed, rainfall simulations reported by Engel *et al.*, (2009) demonstrated marked reductions in suspended sediment concentrations under conservation tillage plots, especially under no tillage. Considering the impact of soil management measures for reducing erosion, alongside hydrological properties such as infiltration and runoff, presents a key wider benefit of NFM.

However, it is important to note that this expanding knowledge base on how soil management practices may reduce flood risk in the UK (as well as provide local, farm-scale benefits), is currently highly variable, dependent on a small quantity of empirical datasets that have quantified these hydrological processes and typically relies on data produced in non-UK based catchments (Holman *et al.*, 2003b; Ngai *et al.*, 2017). The current literature recommends extensive research to generate new empirical datasets to fuel further upscaling and modelling assessments of the impact of soil management measures for flood risk reduction (O'Connell *et al.*, 2007; Boulal *et al.*, 2011; Deasy *et al.*, 2014). Currently, evidence for the impact of subsoiling on infiltration, overland flow and soil erosion, at the local scale is highly variable, subject to numerous factors including the depth and extent of subsoiling, soil type, moisture conditions and state of control soil (Evans *et al.*, 1996; Burgess *et al.*, 2000; Franklin *et al.*, 2007; Truman *et al.*, 2007). Moreover, the benefits of subsoiling are not demonstrated everywhere, for example, with higher overland flow produced in some cases following subsoiling (Sone et al., (2019). Deasy et al., (2014) highlighted that overland flow values may be altered by changing soil management practices, with impacts for flood peak timings. However, these results were constrained by high variability and a need for further runs, for example where minimum tillage was seen to produce increases in discharge total, peak, and duration, as well as in increase in lag time, relative to traditional ploughing.

The variability in the literature reflects the range of spatial and temporal soil hydrological responses across UK catchments. This means that using singular values for soil parameterisation in modelling frameworks can limit efforts to fully reflect the differing impacts that land use change and management have (Evans *et al.*, 1996; Truman *et al.*, 2005; Franklin *et al.*, 2007; Bormann and Klaassen, 2008). This makes the translation of soil hydrological data (eg. infiltration or overland flow values) into different scales and catchments highly uncertain without a sufficient range of runoff and infiltration datasets (Boulal *et al.*, 2011; Deasy *et al.*, 2014). Indeed, modelling studies require empirical datasets containing measured hydrological flux values, to inform, and validate simulations, where relying on assumptions to generate these values, for instance based on roughness estimations (eg. Manning's), may result in over or under-estimations (Bond *et al.*, 2020). The use of measured water fluxes such as overland flow or infiltration can be used to conceptualise a range of catchment types and conditions and present real-world values for comparison (Ngai *et al.*, 2017; Bond *et al.*, 2020). Moreover, there is a need for new empirical datasets to support the conceptualisation and evidence the impact of hydrological processes altered through soil management, to enable future assessments of the impacts of soil management for channel flows and flood risk (Wheater and Evans, 2009; Ngai *et al.*, 2017). Improving understanding of the potential role of soil management methods for flood risk reduction will expand future contributions to catchment-based flood management schemes. Furthermore, by focusing future soil management practices on targeted areas that are contributing disproportionally to runoff production, whole-catchment flood risk may be reduced (Vafakhah *et al.*, 2019).

Therefore, in this chapter, the effects of subsoiling on soil infiltration rates and overland flow generation, were assessed at five farms across the Tone and Parrett catchments, Somerset (SW-England). Physical soil properties were measured in conjunction with single-ring infiltration experiments. A rainfall simulator was used to gain plot-scale overland flow, infiltration rates, and sediment yield data. This dataset enabled analysis of the impacts and in-field variation associated with the impacts of subsoiling, for wider application as a NFM measure.

6.3. Data and methods

The methodological approach taken in this study comprised of field-based testing of soil properties across five farms to compare subsoiled versus controlled field plots. Soils were tested for particle size distribution, soil organic carbon, bulk density, and infiltration rates. In addition, rainfall simulations were conducted to compare overland flow, infiltration, suspended sediment concentration and total sediment yields between subsoiled and controlled plots. These tests were conducted to examine the impact of subsoiling as an agricultural management method for NFM.

6.3.1. Study area

This research was conducted in the Tone and Parrett catchments, SW-England. The Tone drains from Exmoor and the Quantock, Backdown and Brendon hills, joining the River Parrett at Burrowbridge (Environment Agency, 2020). Soil structure is considered degraded in the south-west of England, attributed to intensive agricultural practices and a lack of successful corrective management (Palmer and Smith, 2013). Palmer and Smith's (2013) survey results from 3243 sites across 31 catchments in SW-England highlighted that 38% had high or severe levels of structural damage. These were based on site observations and a classification of soil structure from soil pits dug at each site. For those sites classed as highly or severely degraded, visible compaction or surface soil capping was reported, where dug soils were dense and visibly structureless. In addition, surface water runoff would be evident across the field. The impacts of soil compaction in SW-England are further amplified by higher levels of annual rainfall and sloping topography (relative to the east of England), presenting additional surface runoff amplification risk (Palmer and Smith 2013). Soil degradation assessments here reported 38% of surveyed sites had degraded soil structure and enhanced surface water runoff due to marked soil compaction and decrease in soil pore sizes (Palmer and Smith, 2013).

6.3.2. Field sites and experimental setup

This study investigated subsoiling: a conservation, non-inversion tillage and machinery-based soil management method, term often used interchangeably with flat lifting, ripping and aerating (Akinci *et al.*, 2004). Subsoiling is an agricultural treatment, conducted by farmers to reduce compaction by deep loosening of the soil, largely aimed at increasing rooting depths and increasing water uptake to improve crop yields, particularly in dry conditions (Akinci *et al.*, 2004; Feng *et al.*, 2018; Borek, 2020). Treatments are conducted using a tractor-mounted subsoiler (or flat lifter), which consists of vertical shanks that typically run >30cm deep and shatter the subsoil. This is a different process to 'traditional' ploughing, which inverts the soil at a shallower depth. The effects of subsoiling are typically not expected to be long lasting and therefore repeat treatments may be conducted on farms once every few years, although based on the study area and local knowledge accumulated in this chapter, this practice and period intervals vary widely. Indeed, whilst some farmers may routinely subsoil particular fields or areas at a 2-year interval (eg. Wang *et al.*, 2020), elsewhere it may be employed as a one-off treatment or experiment.

Between 2017 and 2020, subsoiling trials were conducted across the five farm field sites at working farms across the Tone and Parrett catchments (see Figure 6.1). Subsoiling was conducted as part of the Hills to Levels project (see chapter 2), aiming to reduce surface runoff and improve local infiltration and soil health, particularly in catchment headwaters. At all five sites, subsoiling was conducted on a trial basis where fields had been partially managed 'as usual', with the remainder subsoiled to a 30cm depth. Within these catchments, subsoiling was a new method employed by the landowners following discussions and soil husbandry advice through the Hills to Levels project. Subsoiling was largely chosen by farmers to experiment as an alternative to other agricultural management methods, such as crop rotations. Keeping part of the field as a control was a key aspect of this work which allowed for data collection on both the subsoiled and controlled sections of field for comparisons. Prior to the data collection in this study, preliminary data was produced by the Farming and Wildlife Advisory Group, South-West (FWAG-SW) to inform farmers as part of their soil husbandry and wider farm advice network. For the purpose of this study, these five sites were selected in order to ensure a good spread of locations across the study catchments, whilst ensuring that all had applied similar subsoiling treatments, for example using corresponding equipment, with subsoiling to a similar depth.

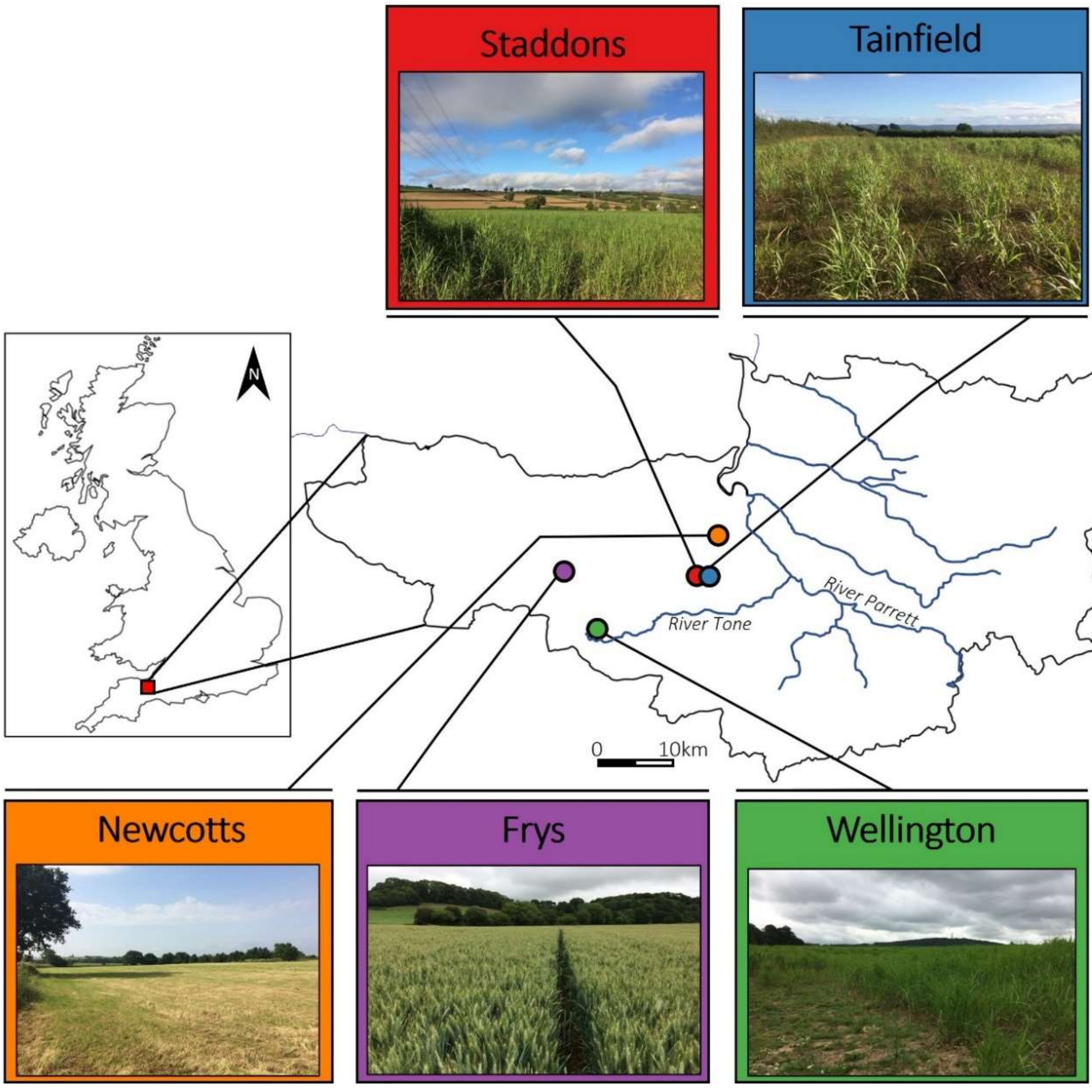

Figure 6.1. Five study sites located across the Tone and Parrett catchments, Somerset (SW-England). Sites are grassland (Newcotts); Winter Wheat (Frys) and Miscanthus (Wellington, Tainfield and Staddons), all with a subsoiled soil trial and controlled field section.

Sampling and testing for bulk density, soil organic carbon, infiltration, overland flow and sediment yield, was conducted, between June 2018 and October 2020 (see Table 6.1 for site summaries). These properties are widely used to characterise soil structure, health, and compaction, which are inherently linked to the water holding capacity of soil (Da Silva *et al.*, 1997). For consistency, all field work was conducted in the summer months.

Site	Location	Crop	Trial start	Testing	Methods
Newcotts	Bridgwater	Grassland	Oct 2017	June 2018	BD, SOM, SI, PD
Frys	Wiveliscombe	Winter wheat	Oct 2017	July 2018	BD, SOM, SI, PD
Wellington	Wellington	Miscanthus	Oct 2018	July - Aug 2019	BD, SOM, SI, PD
Tainfield	Kingston St Mary	Miscanthus	March 2020	Aug - Sep 2020	BD, SOM, SI, RS, PD
Staddons	Kingston St Mary	Miscanthus	March 2020	July - Sep 2020	BD, SOM, SI, RS, PD

Table 6.1. Study sites and soil trial details. Crop refers to the crop type at the time of subsoiling and when field work occurred. Trial start indicates month when soil is subsoiled, whilst testing indicates when fieldwork occurred. Selected methods at each site are indicated, where BD = bulk density, SOM = Soil organic matter, SI = Single-ring infiltration, PD = Particle distribution and RS = Rainfall simulation. Soil refers to soil type extracted from UK soil classification maps from NSRI World Reference Base (UKRI 2021).

From initial, pilot experiements, high field variability for all measurements was clear, for instance in some cases where variability in values within a field section was higher than the differences seen between control and trial field sections. To ensure that this field variability was characterised, a high sample number of tests/cores was initially conducted (21 cores per field type). After the first field season (that comprised of Newcotts and Frys), this sample number was increased to 36 cores per field type. At all sites, sampling and testing was conducted along transects, which covered the full area of the field, where 20cm soil cores were taken using an auger and single-ring infiltration tests carried out. Transects were drawn from the top-centre of each field, with sampling points at 5m intervals, where one cross-shaped transect was used per field type at each site. At Tainfield and Staddons, rainfall simulations on a 1×1m^2 were conducted at marked positions in between transect lines to minimise bias regarding where sampling or testing took place.

This setup was selected to reduce sampling bias, ensure consistency between field sites and secure full inter-field coverage. Figure 6.2 shows the transect experimental setup for field testing, including where rainfall simulation plots were placed in repect to the soil sampling and single-ring infiltration tests. In addition, transect orientation in relation to field slope is indicated here, where one transect lines travels downslope, with the cross travelling across-slope. Therefore, for the rainfall simulator plots, the collection trough of each simulator setup was installed on the downslope side (see Figure 6.2b).

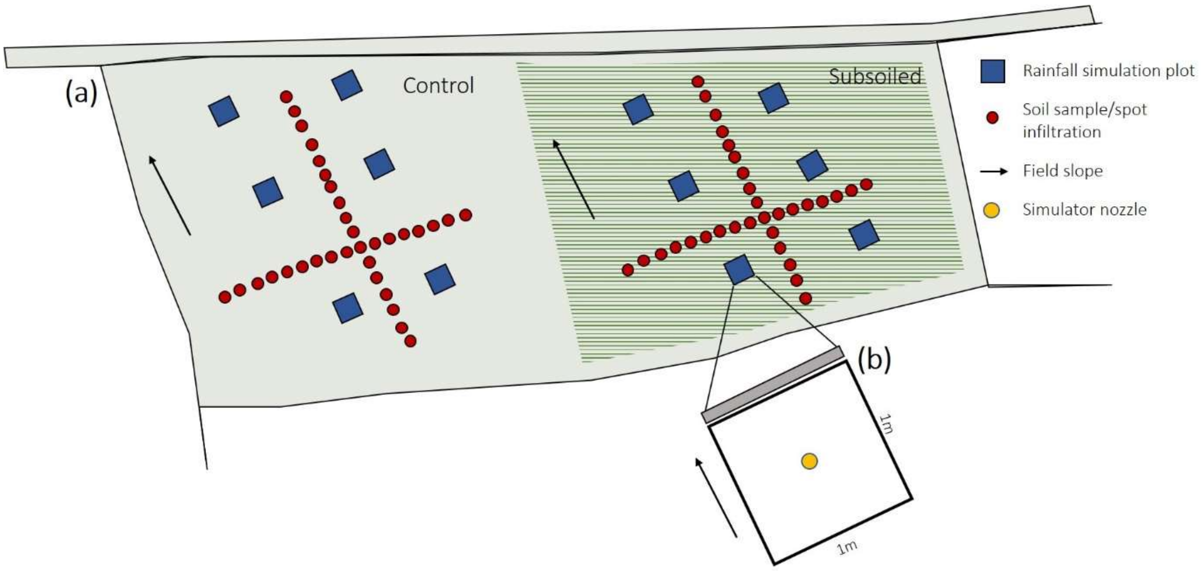

Figure 6.2. Field sampling and testing experimental design, showing the subsoiled versus control trial field site at an arable farm. Transects for soil sampling and single-ring infiltration tests (all sites) are indicated (a). Also detailed is a rainfall simulation setup, where runoff collects downslope in collection trough (b).

6.3.3. Soil particle size distribution

Particle size distribution of the soils in each field type were determined to inform the study on the expected soil characteristics, for instance based on whether the soils are more sand, silt or clay dominated. This will aid comparisons with other catchments and presents a dataset for the study sites at a finer scale than the national soil maps (see chapter 2.2).

Particle size distribution of soils from each farm were determined using dried and sieved (<1mm) soil samples were tested using a Malvern Mastersizer 3000 (pump speed 2,400 rpm, ultrasound 100%) for laser diffraction, using similar methods to Bieganowski, et al. (2010). Very small quantities of oven dried (50ºC, for 48 hours) sample were added to water to reach a 10-20% obscuration, from which 5 measurements per soil core were recorded. Soil particle distributions were separated into texture classes, based on the Unified Soil Classification System (USCS), recording the percentages of sand (0.075 – 2 mm), silt (0.002-0.075mm), and clay (<0.002mm) (Asenso *et al.*, 2019).

The soil particle size distributions for each site, along with each control and subsoiled area are presented by Figure 6.3. Soils at all field sites are predominately (64-88%) silt, with sand proportions between 10 and 33%, and very small proportions of clay (max 2%). No significant inter-field differences in particle size distribution (between subsoiled and controlled areas) are shown, with only small inter-field variation presented. Some particle size distribution differences were highlighted between sites, most notably between Newcotts (subsoiled plot mean sand proportion of 9.6%) and Frys (subsoiled plot mean sand proportion of 33.24%).

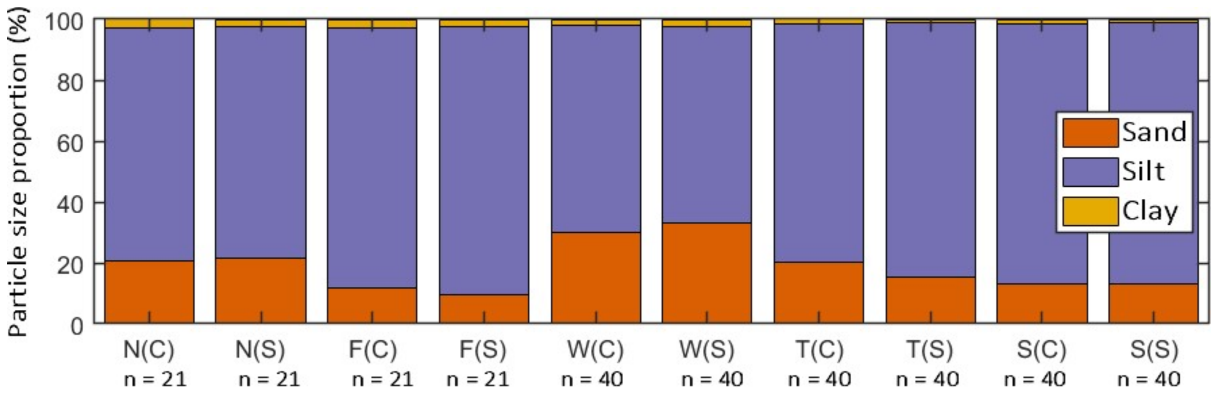

Figure 6.3. Soil particle size distribution (clay, silt, and sand), where N = Newcotts, F = Frys. W = Wellington, T = Tainfield and S = Staddons, (C) = control and (S) = subsoiled.

6.3.4. Soil organic carbon

Soil organic carbon (SOC) is an important indicator of soil health and structure, and its ability to store water (Howard and Howard, 1990). Loss on ignition (LOI) is a widely applied method for quantifying SOC (Hoogsteen *et al.*, 2015), as its rapid and inexpensive compared to other methods (eg. wet chemical oxidation (Konen *et al.*, 2002)). LOI was employed, based on the notion that by removing all carbon from a sample, the weight difference before and after combustion will indicate the percentage carbon that the sample contains (Ball, 1964; Howard and Howard, 1990). Using each core, a 5g ground sample of oven dried (50°C, for 48 hours) soil was combusted in a muffle furnace for 360°c for 2 hours (Ball, 1964; Konen et al., 2002). A higher temperature was not used to avoid introducing additional weight losses (eg. from clay minerals (Davies, 1974)). Eqn. 1 was used to determine the soil organic carbon percentage of each soil sample, where SOC = soil organic carbon (%), MD = Soil mass pre-combustion (g) and MC = Soil mass post-combustion (g).

$$\mathrm{SOC} = \frac{\mathrm{MC} - \mathrm{MD}}{\mathrm{MD}} \mathrm{x} 100 \qquad \text{eqn. 1.}$$

6.3.5. Bulk density

Soil dry bulk density quantifies mass per volume of dry soil (Lestariningsih *et al.*, 2013). Higher values indicate compaction, poor soil structure, reduced infiltration and water storage capacity (Da Silva *et al.*, 1997). The volumetric ring method was used here, where vegetation and surface soil were cleared and the ring (65cm^3 volume) inserted into the surface (Lestariningsih *et al.*, 2013; Lunka and Patil, 2016). The core was excavated carefully to minimise soil loss and then dried (50ºC, until no further weight loss occurred). Bulk density was calculated using eqn. 2, where BD = bulk density (g cm^3), M = oven dried soil mass (g) and V = bulk density ring volume (cm^3).

$$\mathrm{BD} = \frac{\mathrm{M}}{\mathrm{V}} \qquad \text{eqn. 2.}$$

6.3.6. Single-ring infiltration

Soil infiltration rate represents the rate at which water flows vertically through the surface layer of the soil. Over time and as soil gets progressively wetter, an exponential decline in infiltration rate is expected. Two-hundred and eighty (280) single-ring infiltration tests across the five farms were carried out to determine localised ponded infiltration rates. The number of tests varied between farms. For the first field season, 16 tests per control and subsoiled field section were completed for Newcotts and Frys. For Wellington, 36 tests were carried out as a higher number was favoured to allow for greater consideration of in-field variation. For the third field season (at Tainfield and Staddons), 20 tests were conducted, to supplement plot-scale rainfall simulations (see section 6.3.7). Infiltrometer rings (9503mm^2 area) were inserted evenly into the soil, ensuring minimum disturbance at a 5cm depth. A Mariotte bottle was used to dispense water at a constant rate to the ring. Water ponding over the soil surface was typically around 15 cm depth to the soil surface. Volume change (ml) in the Mariotte bottle and time were recorded until a steady state in the rate of volume change was reached (Lili *et al.*, 2008), which for these tests took from 30-60 minutes to reach. Volume change in the Mariotte bottle (ml) was converted to mm based on the infiltration ring area, by dividing the volume change (mm^3) by the area of the infiltration ring ($9503mm^2$). Then, infiltration rate was calculated using eqn.3, where ΔL = water level change between measurements (mm), T = time between measurements (min) and V = volume of water per mm of water level change (ml/mm). Subsequently, a mean was taken of the steady state values (once the initial infiltration rapid increase levelled out) to gain a final (steady) infiltration rate value for each test.

$$IR = \frac{\Delta \mathrm{L}}{\mathrm{T}} \times \mathrm{V} \qquad \text{eqn. 3.}$$

Single ring infiltrometers were used in this study due to their ease of use, their portability, and availability of comparable secondary data in the literature (McKenzie and Coughlan, 2002; Lili *et al.*, 2008). They have a simple design and installation, allowing multiple tests to occur at once and a high sample number. However, there are limitations associated with single ring infiltrometers, principally that they represent ponded water infiltration rate, rather than rainfall infiltration. In addition, in reality they represent a very small area, can be associated with high surface disturbance and are likely to overestimate infiltration because of high rates of unconstrained lateral flow. This error source may be reduced using a double-ring infiltrometers, however this method would not allow such rapid replicability (Rice *et al.*, 2014). To ensure consistency between tests and reduce potential human-induced increases or decreases in water loss, a constant insertion depth was used to 15cm. In addition, a seal of soil around the ring rim was ensured to reduce lateral flow. A level area was chosen for each test, with the surface soil cleared and a constant water supply prepared.

6.3.6. Rainfall simulations

Twenty-four (24) small-scale rainfall simulations were carried out to characterise the infiltration, overland flow, and sediment yields in control and subsoiled plots. Rainfall simulations can produce constant, repeatable rainfall conditions over a small plot area (Iserloh *et al.*, 2012). Properties such as event duration, drop size, velocity, intensity and area can be controlled to a study's specification, with no need to rely on spatially and temporally variable natural rainfall events (Clarke and Walsh, 2009; Iserloh *et al.*, 2012). Rainfall simulators have been widely deployed in the literature, typically aiming to study impacts on runoff, erosion, and infiltration (Perkins and McDaniel, 2005). Simulations can be conducted in laboratory conditions, offering further control on timing, evaporation, wind, and equipment regulation as well as a larger spatial scale. However, small, portable rainfall simulators are practical, fast and cost-effective solutions to gain measurements in a variety of terrains (Szabó *et al.*, 2020).

In this study, a simple, small-scale simulator was used (designed by Ellis, 2022), suitable for a 2-person assemblage and operation. The design was based on simulators outlined in Abudi, Carmi and Berliner (2012) and Iserloh *et al.* (2012), consisting of a 1m^2 aluminium frame, from which a full cone (120° spray), pressurised nozzle (Lechler 46048430CA001) was attached at the centre (1m height above surface) for uniform rainfall (approx. 2mm drop size). In the literature, rainfall simulator plots are reported up to 5x10m^2 (Esteves *et al.*, 2000). However, that model of design would have been too large to manage here as all sites were located on working, arable fields, where crops were up to 1m high in places at the time of fieldwork and care had to be taken to mitigate any damage. In addition, a small size frame offers many advantages in terms of relative efficiency and ease of assembly with 2 people, compared to larger setups which may require multiple people and a far longer setup time in between simulations, reducing time for data collection. Three sides of the frame were controlled with aluminium sheets (0.3 x 1m), inserted 15cm into the soil, to reduce lateral flow and ensure a controlled plot area. On the fourth side, a 1x0.5x0.6m trough was dug outside of the frame, where soil was removed. A runoff collection drain (1x0.3m PVC gutter) was carefully inserted, with the lip 4-5cm beneath the soil surface, ensuring a gentle slope, down to a further 0.2x0.5x0.8m pit for the runoff collection container. To avoid direct rainfall collection from the nozzle, the gutter was covered during simulations.

Rainfall was generated using a 12V pump (Shurflo 2095-204-413), powered by a 12V leisure battery. In laboratory conditions, a constant rainfall rate of 40mm/hr was achieved, based on a constant pressure, maintained at 1.25bar (14.5-21.8 psi). This intensity was chosen as it is the maximum rainfall intensity recorded from 2018-2020 at a local rain gauge (see chapter 3.5) to ensure that simulations were typical of a high magnitude rainfall event in the Tone catchment. However, in field conditions, maintaining this constant rainfall rate was challenging where small pressure changes (1-1.5bar) and external conditions meant that variable rainfall totals between simulations occurred. Therefore, whilst the rainfall simulator was calibrated prior to use, by adjusting the pressure dials, a constant rainfall intensity proved difficult to achieve in the field without very regular calibration (Panachuki *et al.*, 2011). Therefore, 4 rain gauges (100mm diameter) were also positioned in the 4 plot corners (10cm distance from edge) to measure simulated rainfall quantities. Through each simulation, the rainfall total was recorded at a 5-minute interval for each gauge, where a mean was taken using the 4 rainfall datasets to gain the final simulation rainfall timeseries. The total runoff was then divided by the total event rainfall for each simulation to gain a runoff coefficient for each simulation.

Figure 6.4 illustrates the key setup and simulation steps. For each simulation, the frame was constructed on a gentle slope (4-6°). Slope was measured within each simulation plot using a clinometer, where 5 readings were taken for each $1m^2$ plot, which were averaged to gain one value per simulation. On the downslope side, the surface runoff collection trench was dug. Simulations were conducted for 70 minutes, with surface runoff measured at a 1-minute timestep and bottled at a 5-minute timestep. Soil moisture was recorded pre and post simulation, using a ThetaProbe soil moisture sensor, which was inserted to a 10cm depth. In addition, the vegetation and crop coverage for each plot was documented. Simulated rainfall was recorded at a 1-minute timestep and averaged between all four gauges at the end of each simulation. Infiltration rate was calculated as the difference between rainfall and surface runoff (Dimanche and Hoogmoed, 2002).

In the lab, bottled runoff samples were filtered using pre-weighed filter paper. The deposited sediment was then oven dried (30°C, 3 hours) and re-weighed and subtracted from the filter paper weight, to gain total sediment concentration per runoff volume. Suspended sediment concentration (SSC, g/cm) was calculated using eqn. 4, where M = sediment mass (g) and V = runoff volume (cm^3).

$$SSC\ (g/cm) = \frac{M}{V} \qquad eqn. 4.$$

Subsequently, sediment flux (SF, g) was calculated using eqn. 5, where SSC = suspended sediment concentration (g/cm) and Q = surface runoff discharge (mm).

$$SF\ (g) = SSC\ X\ Q \qquad eqn. 5.$$

Finally, to gain the total amount of sediment lost over the duration of each simulation, sediment yield (SY, g) was calculated using eqn. 6., where SSC = suspended sediment concentration (g/cm^3), R = runoff (mm) and F = time section represented by sediment yield (min).

$$SY\ (g) = (SSC\ \times (R/F)\ \times\ F \qquad eqn. 6.$$

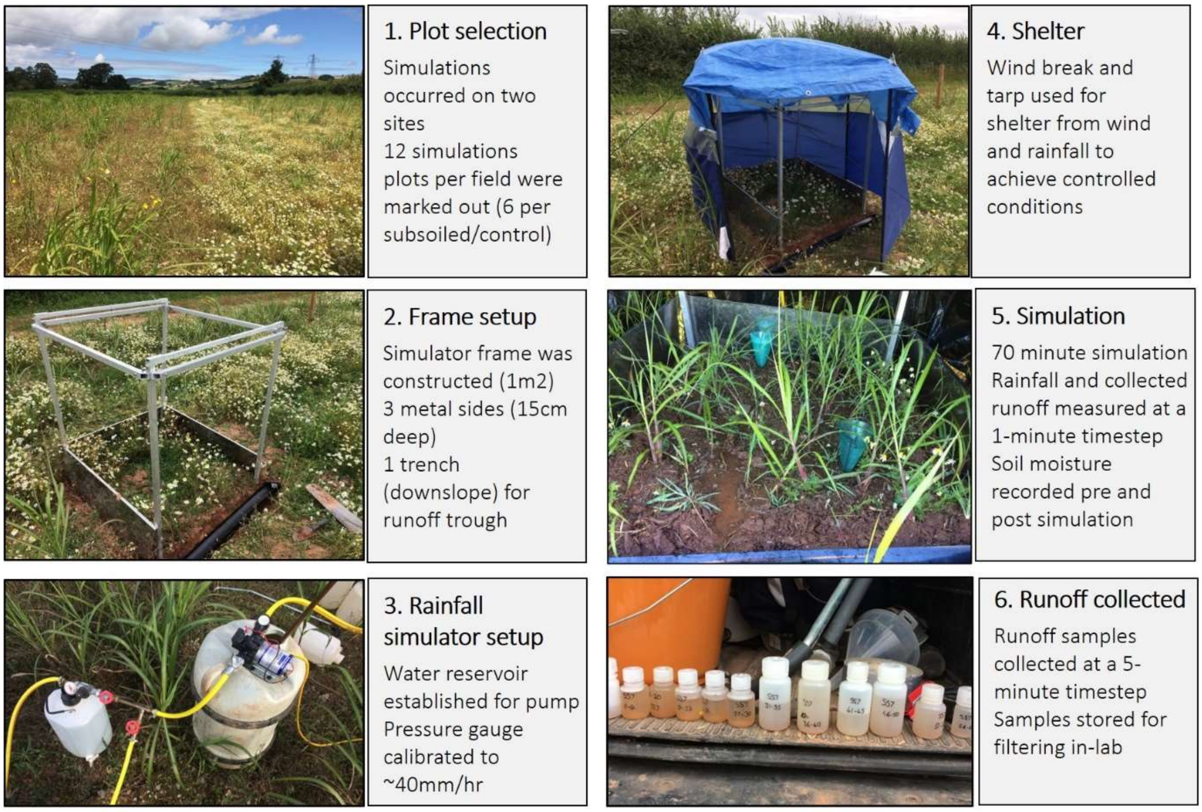

Figure 6.4. Workflow of key rainfall simulation steps from setup to data collection.

6.3.7. Statistical testing

In order to test for differences in soil organic carbon, bulk density, and single-ring infiltration rates between the controlled and subsoiled fields statistical testing was used. This was based on the hypothesis that soil organic carbon will be higher in the subsoiled fields, bulk density, will be lower than the controlled, and infiltration rates will be higher in the subsoiled than the controlled. Tests were conducted separately for the single-ring infiltration and the rainfall simulations due to their different samples sizes and different assumptions/set ups.

First, a one-sample Kolmogorov-Smirnov (K-S) test was conducted to determine data normality. This was used to determine whether a parametric or nonparametric statistical test should be conducted. If the data were normally distributed, a parametric test should be conducted, for instance to compare differences in group means (eg. t-test). Conversely, if data were deemed to be non-normally distributed, a nonparametric statistical test is best as this allows for comparisons to be made without assumptions about data distribution.

Using a one-sample K-S test, all datasets were found to be non-normally distributed. Therefore, a the Wilcoxon rank sum (a non-parametric test) was used to determine the whether there is any significant difference between two samples (subsoiled and control from each study site). This was based on a comparison of the median values of each sample, where a p-value determines the significance.

Where data were analysed to consider whether two variables are related, Pearson's correlation coefficient (r) was taken to extract the type of correlation present, specifically a negative correlation (close to -1), no correlation (close to 0) or a positive correlation (close to 1). In addition, the r^2 value indicates the amount of variability depicted by the correlation line, for instance where a value closer to 1 depicts a closer fit and less variation.

6.4. Results

The impacts of subsoiling are illustrated through comparisons of soil organic carbon (Figure 6.5) and soil bulk density results (Figure 6.6). These are supplemented with singled-ring infiltration results (Figures 6.7-6.8), and finally infiltration, runoff, and erosion results from rainfall simulations (Figures 6.9-6.14).

6.4.1. The impact of subsoiling on soil organic carbon

Subsoiled conditions show increased soil organic carbon (SOC) in 4 out of 5 farms: Newcotts, Wellington, Tainfield and Staddons, with significant increases ($p < 0.05$, Wilcoxon rank sum test) in SOC shown by 3 farms (up to 19.1% increase). At Frys farm, SOC decreases under subsoiling (-8.98%), although this is not significant ($p = 0.27$). See Figure 6.5 for plotted soil organic carbon value comparisons across all sites.

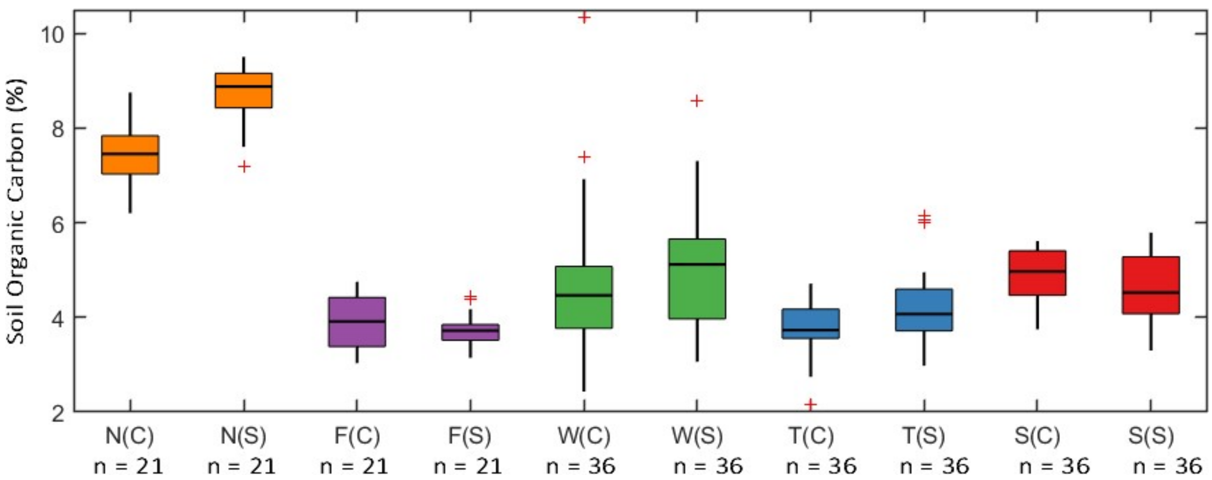

Figure 6.5. Soil organic carbon for each field site, where N = Newcotts, F = Frys, W = Wellington, T = Tainfield, S = Staddons, (C) = control and (S) = subsoiled.

6.4.2. The impact of subsoiling on bulk density

Subsoiled fields show large significant reductions in bulk density at Tainfield and Staddons (19.7% ($p < 0.05$) and 16.87% ($p < 0.05$) decreases respectively). Frys and Wellington sites show smaller (8.18 and 11.86%) decreases in bulk density under subsoiling. The bulk density decreases at these four sites are all statistically significant ($p < 0.05$, Wilcoxon rank sum test). On the other hand, Newcotts shows a small (4.75%) increase in bulk density, although this is not significant ($p = 0.33$). See Figure 6.6 for plotted soil bulk density value comparisons across all sites.

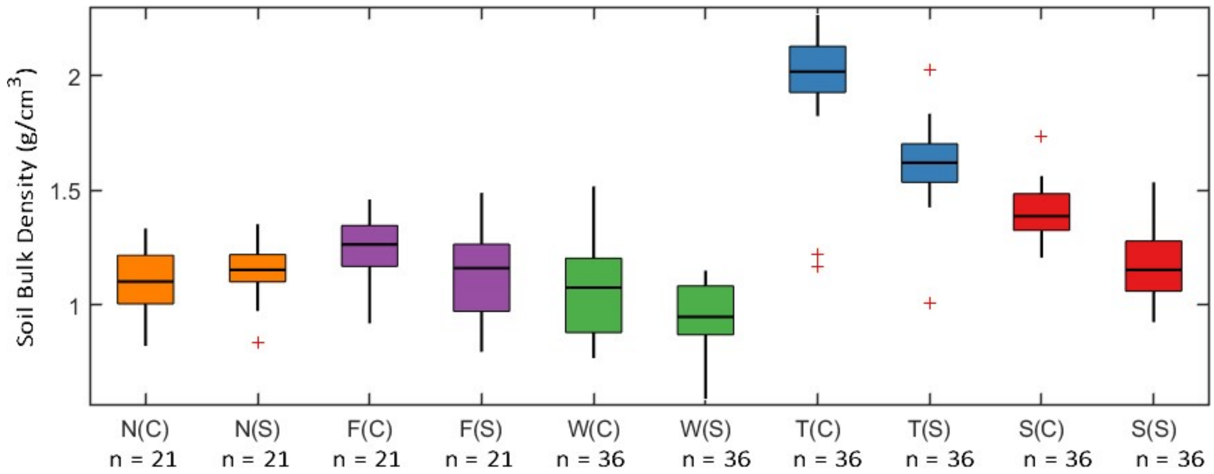

Figure 6.6. Soil bulk density for each subsoiled and control section, where N = Newcotts, F = Frys. W = Wellington, T = Tainfield, S = Staddons, (C) = Control and (S) = Subsoiled.

6.4.3. The relationship between soil physical properties and single-ring infiltration

Results showed that Wellington, Tainfield and Staddons (all miscanthus crop) all present significant ($p < 0.05$) increases (based on a Wilcoxon rank sum test) in infiltration rates under subsoiling, in comparison to control field sections, with median percentage increases of 104%

(Wellington), 605% (Tainfield) and 375% (Staddons). Newcotts presents a small increase and Frys illustrates a small decrease under subsoiling in infiltration rate, although these changes are not statistically significant. See Figure 6.7 for results of infiltration tests across all sites. Median infiltration rates (mm/hr) varied markedly between sites: between 23.3mm/hr (Tainfield, control) and 395.4mm/hr (Frys, control). Table 6.2 presents a summary of key values for bulk density, soil organic carbon and infiltration rate.

Site	Trial	Bulk density (g/cm^3)		Soil organic carbon (%)		Final infiltration rate (mm/hr)	
Newcotts	Subsoiled mdn	1.15		8.9		46.2	
	Control mdn	1.10		7.5		45.7	
	Mdn % change	**4.75**	p = 0.33	**19.11**	p <0.05	**1.19**	p=0.42
Frys	Subsoiled mdn	1.16		3.9		308.1	
	Control mdn	1.26		3.7		395.4	
	Mdn % change	**-8.18**	p <0.05	**4.98**	p=0.27	**-22.1**	p=0.43
Wellingt on	Subsoiled mdn	0.95		5.11		47.7	
	Control mdn	1.07		4.47		23.3	
	Mdn % change	**-11.86**	p <0.05	**14.62**	p <0.05	**104.93**	p <0.05
Tainfield	Subsoiled mdn	1.62		4.07		243.6	
	Control mdn	2.02		3.73		34.5	
	Mdn % change	**-19.7**	p <0.05	**9.11**	p <0.05	**605.24**	p <0.05
Staddons	Subsoiled mdn	1.15		4.52		111.3	
	Control mdn	1.39		4.97		23.4	
	Mdn % change	**-16.87**	p <0.05	**-8.98**	p=0.09	**375.51**	p <0.05

Table 6.2. Soil bulk density, soil organic matter and final rates for each site. Median (mdn) % change indicates percentage change in median values from control to trial field. P-value is indicated as the statistical significance of the data based on Wilcoxon rank sum test (chosen as nonparametric test for non-normally distributed datasets).

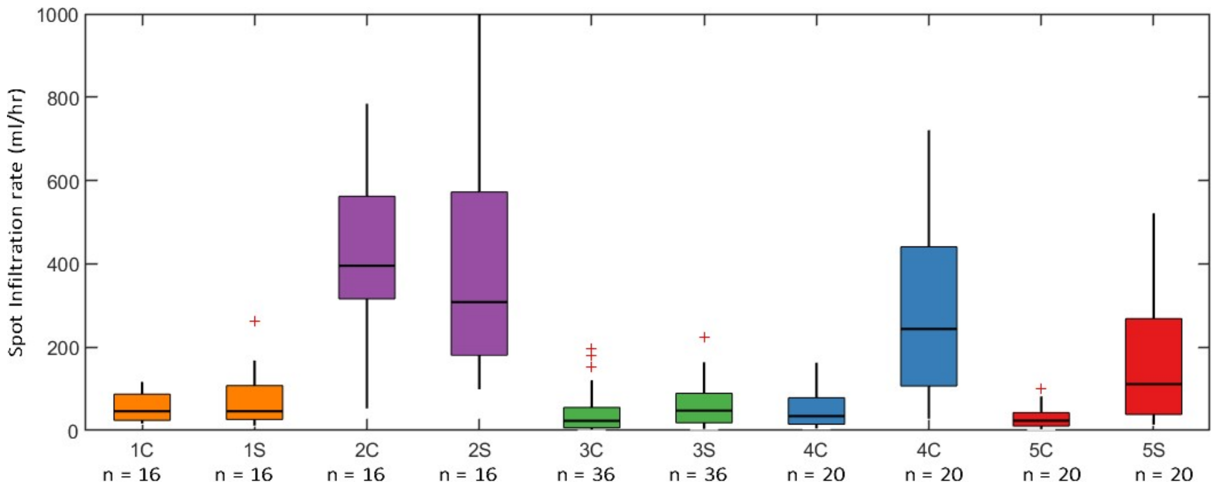

Figure 6.7. Final infiltration rates derived from single-ring infiltrometer tests for each study site, where N = Newcotts, F = Frys. W = Wellington, T = Tainfield and S = Staddons, (C) = Control and (S) = Subsoiled.

Pearson's rank correlation was applied to determine the presence of a linear relationship between, bulk density and final infiltration rate (infiltrometer), and between bulk density and soil organic carbon (see Figure 6.8). All correlations were negative between final infiltration rates (infiltrometer) and bulk density. Similarly, all correlations were negative between soil organic carbon and bulk density. Tainfield demonstrates the largest correlation, where single-ring infiltration rates and bulk density correlation produced a r= -0.82, and a r^2 =0.68. For bulk density and soil organic carbon, this produced a r = -0.85 and a r^2 = 0.72. Correlations for Staddons between soil organic carbon and bulk density are notably small however (-0.17), with very high variation (r^2 = 0.03).

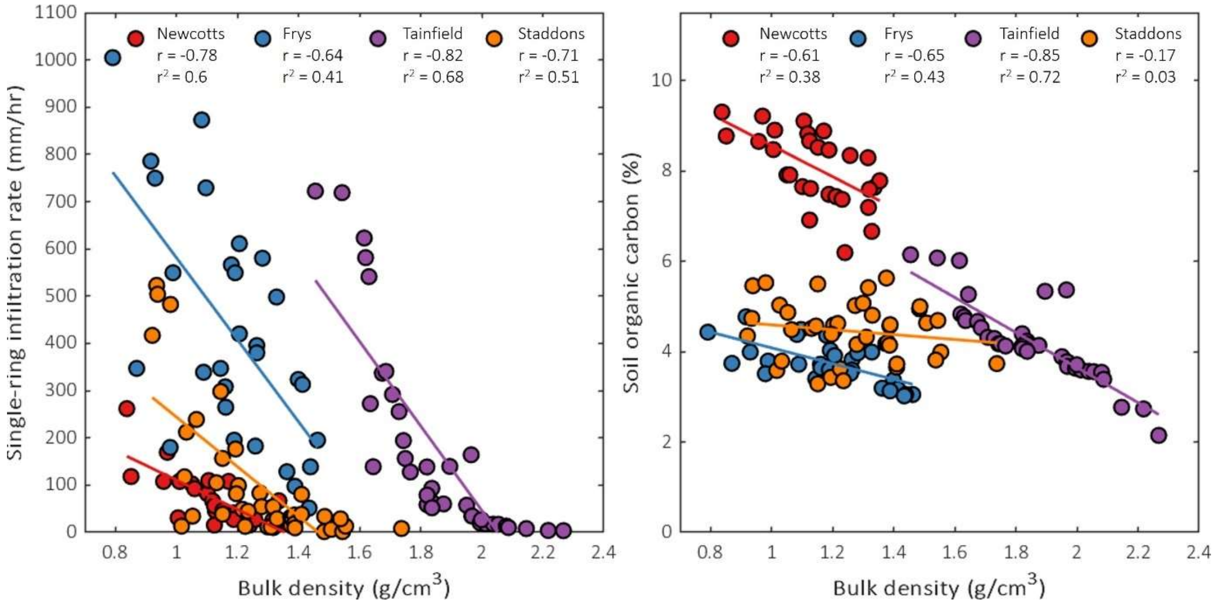

Figure 6.8. Relationship between single-ring infiltration rate, bulk density, and soil organic carbon for Newcotts, Frys, Tainfield and Staddons. Each single soil sample (for bulk density and soil organic carbon) and single-ring infiltration tests were conducted in a quadrat (1m2) along the same transect. Each scatter point represents one sample (soil core) or single-ring infiltration test, where all control and subsoiled results are plotted collectively. Wellington is omitted as due to dense crop coverage at this site, it was difficult to ensure that infiltration tests and soil samples were taken in the same m2 quadrat. Pearson's coefficient (r) and coefficient of determination r2 values are indicated on each plot.

6.4.4. The impact of subsoiling on plot-scale overland flow

A total of 24 rainfall simulations were conducted across sites 4 and 5 (6 simulations per control or subsoiled section) between July and September 2020. Key details from all simulations are summarised by table 7.3.

Site		Simulation	Date	Slope (°)	Plot cover	Pre moisture (%)	Post moisture (%)	Rain-fall (mm)	Over-land flow (mm)	Runoff coefficient
Tainfield	**Control**	**1**	28/07/2020	3.9	Weeds	14.5	38.5	33.5	0.12	0.004
		2	04/08/2020	4.6	Weeds	7.5	33.8	46.1	0.147	0.005
		3	05/08/2020	3.8	Weeds	7.6	30.5	42.4	0.393	0.009
		4	26/08/2020	4.8	Weeds	5.4	39	43.5	1.349	0.03
		5	05/09/2020	4.0	Sparse	7.2	34.8	26.5	0.11	0.004
		6	06/09/2020	3.9	Weeds	7	22.7	46.25	0.777	0.017
	Subsoiled	**1**	28/07/2020	4.0	Weeds	5.8	22.1	33.5	0.13	0.004
		2	29/07/2020	4.5	Weeds	8.5	31.4	27.2	0.44	0.01
		3	05/08/2020	3.8	Weeds	3.1	27.8	39.2	0.115	0.003
		4	26/08/2020	5.5	Weeds	3.8	22.4	46	0.446	0.01
		5	26/08/2020	3.9	Sparse	2.8	35.5	45.7	0.47	0.01
		6	05/09/2020	6.2	Weeds	15.2	34.1	43.1	0.276	0.006
Staddons	**Control**	**1**	30/07/2020	5.5	Sparse	16.3	29.4	35.7	0.372	0.010
		2	08/08/2020	5.8	Sparse	7.5	24.6	43.1	2.889	0.067
		3	08/08/2020	4.9	Sparse	7.2	34.9	44.15	0.379	0.009
		4	10/08/2020	6.0	Sparse	22.2	24.9	43	0.631	0.015
		5	10/08/2020	5.5	Crop	15.3	24.5	45.3	1.455	0.032
		6	04/09/2020	5.9	Crop	13.3	24.6	35.9	1.03	0.029
	Subsoiled	**1**	30/07/2020	6.4	Grass	2.9	26.9	41.7	0.119	0.003
		2	31/07/2020	6.4	Sparse	2.5	26.1	34.3	0.127	0.004
		3	08/08/2020	4.5	Crop	4	27.1	41	0.224	0.005
		4	09/08/2020	5.3	Crop	15.4	25.1	33.25	0.325	0.010
		5	09/08/2020	4.9	Sparse	10	28.7	42.5	0.334	0.008
		6	04/09/2020	5.7	Grass	15.4	29.6	39.35	0.539	0.014

Table 6.3. Details of 24 rainfall simulations (70 minutes duration). Plot cover is grass (no crop, heavy grass coverage) weeds (no crop, light weed coverage), sparse (crop) (up to 5 miscanthus plants) or crop (higher coverage of miscanthus). Pre and post moisture percentages taken within the simulation plot before and after each simulation respectively.

Figure 6.9 illustrates the cumulative overland flow, relative to cumulative simulated rainfall across all rainfall simulations. This depicts how much simulated rainfall becomes overland flow. Overall, the results showed more overland flow generated under controlled plots compared to subsoiled plots. To compare cumulative runoff against 40mm of cumulative rainfall, Tainfield controlled plots presented the highest cumulative runoff termination at 1.2mm and for a Tainfield subsoiled plot, the highest cumulative runoff termination is at 0.45mm of runoff. This difference between subsoiled and controlled plots is larger for Staddons, where for a controlled plot, the highest cumulative runoff termination is at 2.4mm of runoff and for a subsoiled plot, the highest cumulative runoff termination is smaller at 0.55mm (again, to compare to 40mm of cumulative rainfall).

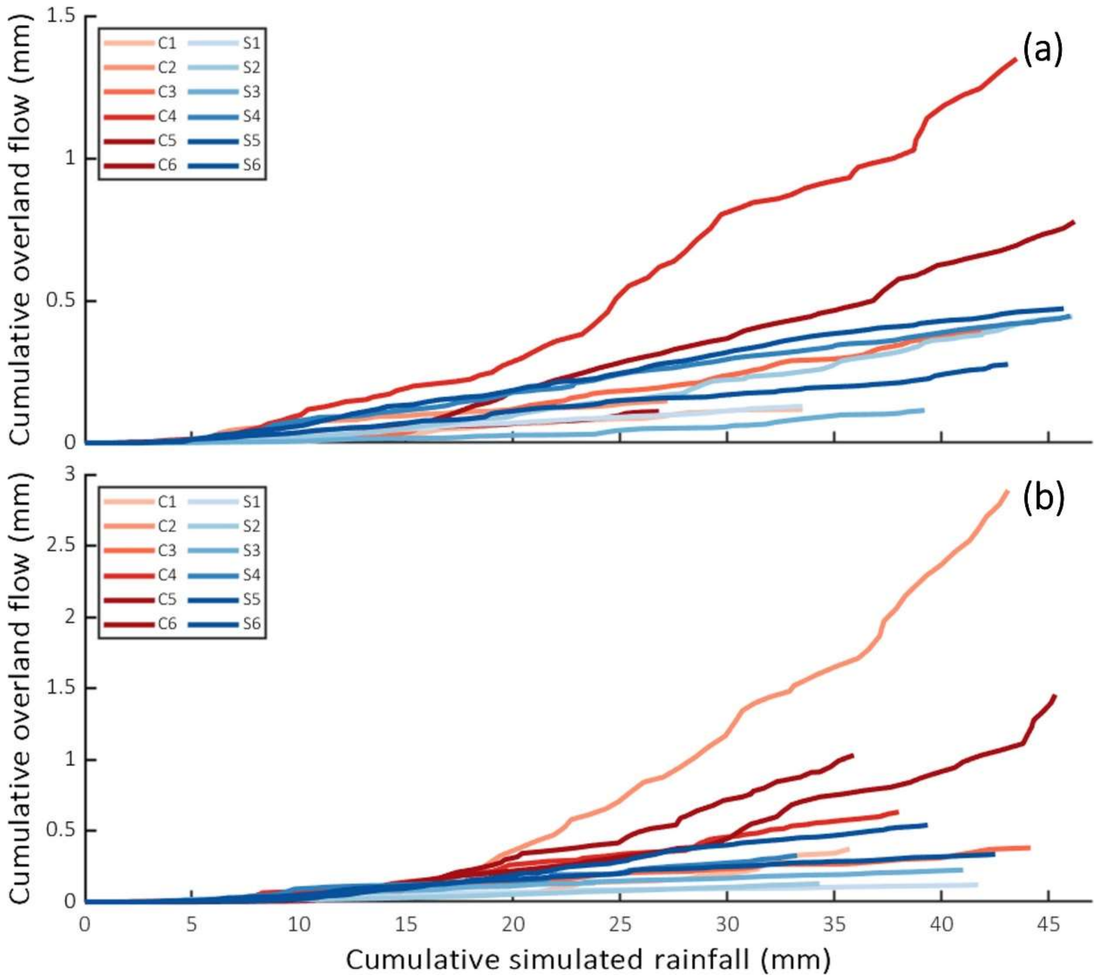

Figure 6.9. Cumulative overland flow (mm) versus cumulative rainfall (mm) for Tainfield (a) and Staddons (b). Simulations are detailed as S (subsoiled) or C (control) and numbered 1-6.

In addition, overland flow, and cumulative rainfall time series for Tainfield and Staddons and each rainfall simulation are illustrated by Figure 6.10. For subsoiled plots, overland flow occurs at a steady rate throughout most of the simulations, whilst for controlled plots with higher overland flow, these values increase with time through the simulation.

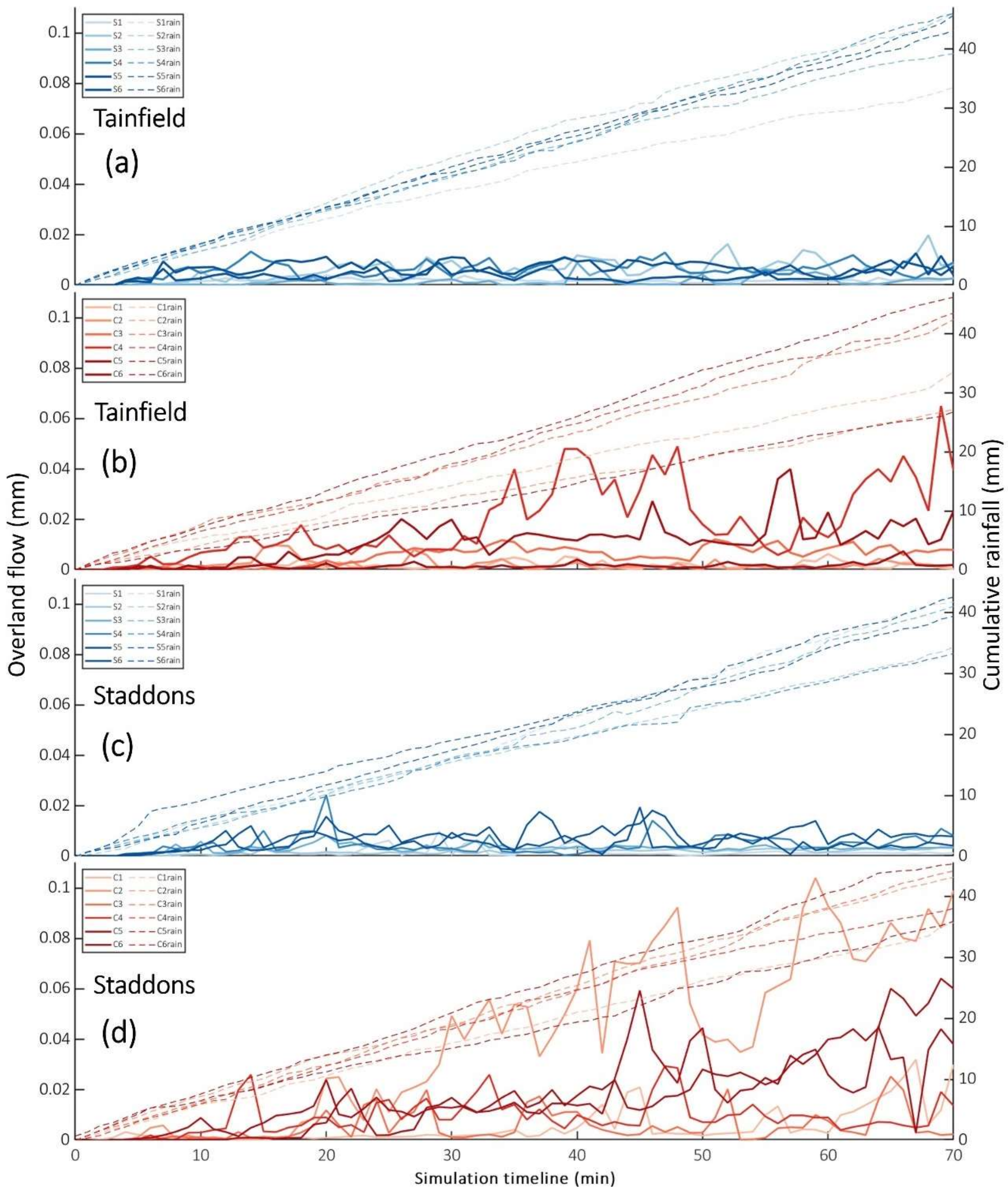

Figure 6.10. Overland flow (mm/min) at a 1-minute timestep for Tainfield and Staddons. Simulations are detailed as S (subsoiled) or C (control) and numbered 1-6

Total rainfall across all simulations varied and thus overland flow values were converted to runoff coefficient and infiltration values. At both sites, lower runoff coefficients were produced from subsoiled plot simulations, with runoff coefficient values of up to 0.113 for a Staddons subsoiled plot, compared to 0.32 for a Staddons controlled plot (Figure 6.11). For Tainfield, runoff coefficients were up to 0.031 for a control, and up to 0.01 for a subsoiled plot. However, all 4 scenarios (control and subsoiled for Tainfield and Staddons respectively), presented high value ranges, especially for controlled plots.

Secondly, steady state infiltration was calculated based on the mean infiltration rate in the final 30 minutes of each simulation. Results showed higher mean steady state infiltration rates in the subsoiled plots, for both sites, although this was not significant (Figure 6.11). This showed a 4.7mm/hr and 4.6mm/hr steady state infiltration rate increase under subsoiling for Tainfield and Staddons respectively, relative to controlled plots. Finally, the time to overland flow initiation was calculated to consider whether subsoiling impacted on runoff response time. Overall, very minimal differences were recorded between the two sites and between subsoiled and controlled plots, where a median of 4.5 minutes for the time to overland flow initiation was recorded for all.

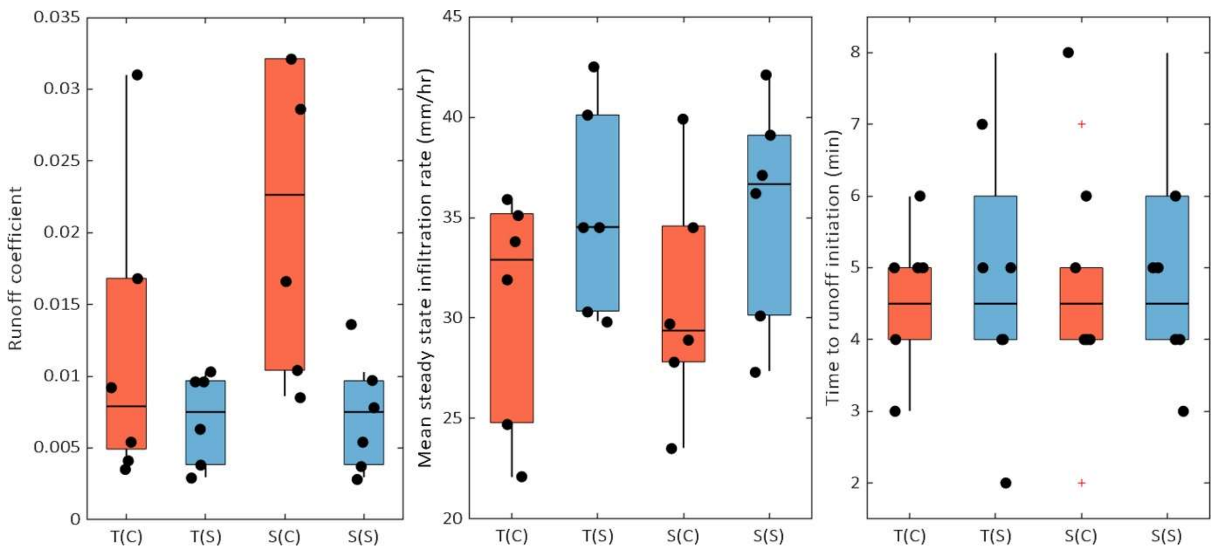

Figure 6.11. Box plots depicting runoff coefficient, mean infiltration rate at steady state (50-70 mins of each simulation) and time to runoff initiation (scatter dot per simulation).

The infiltration rates produced from single-ring infiltration tests and those from rainfall simulator methods were compared (see Figure 6.12). This illustrated that single-ring infiltration values were far higher than those produced from rainfall simulations, for instance in some cases, by an order of magnitude. This was particularly noticeable for subsoiled tests at both sites, where median infiltration rates were 194.2mm/hr and 81.8mm/hr for Tainfield and Staddons respectively, compared to 34.6mm/hr (Tainfield) and 36.2mm/hr (Staddons) for rainfall simulation methods. For controlled tests, these differences were still marked, although not as large, where for Tainfield, median infiltration rates were 20.1mm/hr for single-ring methods and 31.98mm/hr for rainfall simulator methods. For Staddons, median infiltration rates were 14.3mm/hr for single-ring methods and 29.8mm/hr for rainfall simulator methods.

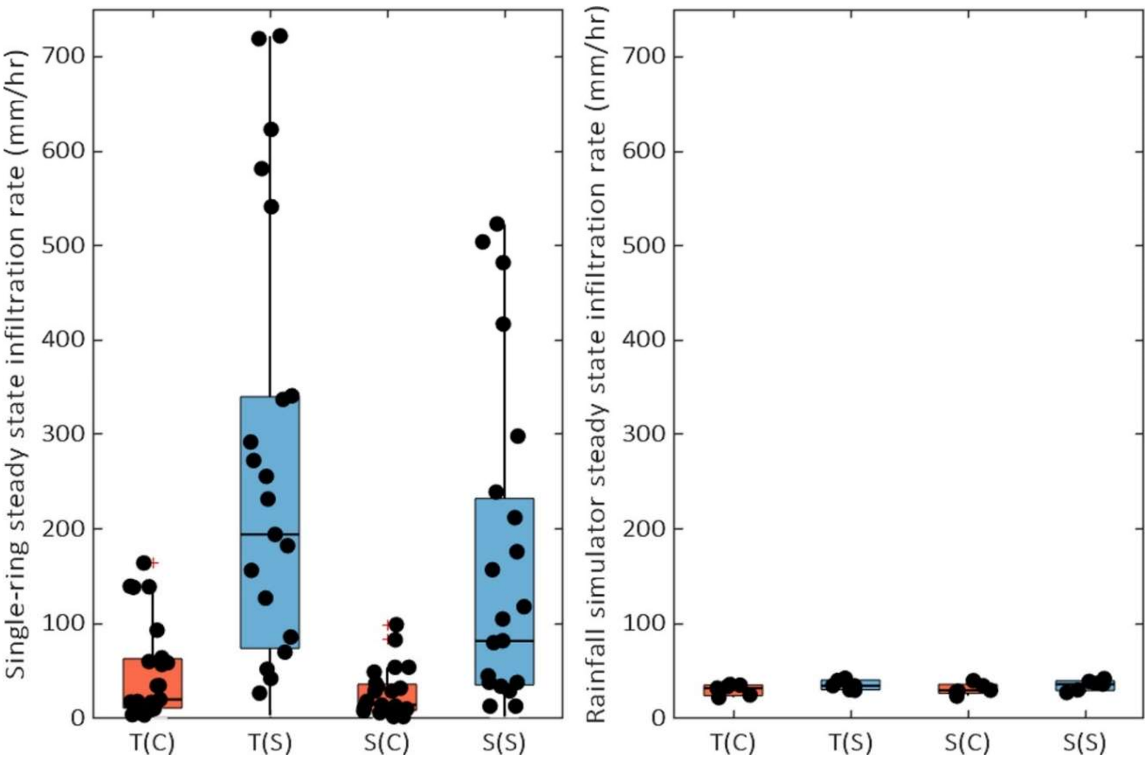

Figure 6.12. Comparison infiltration values gained from single-ring infiltration tests and rainfall simulations. Extracted is the mean steady state infiltration rate value for each simulation, which is plotted against a mean of the nearest 6 single-ring infiltration tests per field.

6.4.5. The impact of subsoiling on plot-scale sediment loss

Figures 6.13 and 6.14 illustrate the impact of subsoiling on suspended sediment concentrations, sediment flux and sediment yield for each simulation. Suspended sediment concentrations vary markedly across all simulations but notably the highest concentrations most commonly within the first 20 minutes of all simulations (17/24 simulations), see Figure 6.14. Later in the simulations suspended sediment concentration typically reduce and level out. TC6 and SC1 present a markedly higher spike in suspended sediment concentration at 10 minutes of 0.21 and 0.1 cg/cm^3, respectively (see Figure 6.13), although it is important to note that this is based on one sample and is not reflective of the whole simulation.

Results also show that controlled plots have overall higher sediment yields, compared to subsoiled plots for both sites (see Figure 6.13). However, importantly these produced sediment yields are associated with high variability, for example Staddons controlled plots present sediment yield values between 0.0002 and 0.5g. Subsoiled plots at both sites present consistently low sediment yield values (maximum of 0.001g for Tainfield and Staddons subsoiled). Indeed, most noticeable are the sediment yields for TC4, SC1 and SC4 which are up to 0.52g higher than the next highest control value (0.01g).

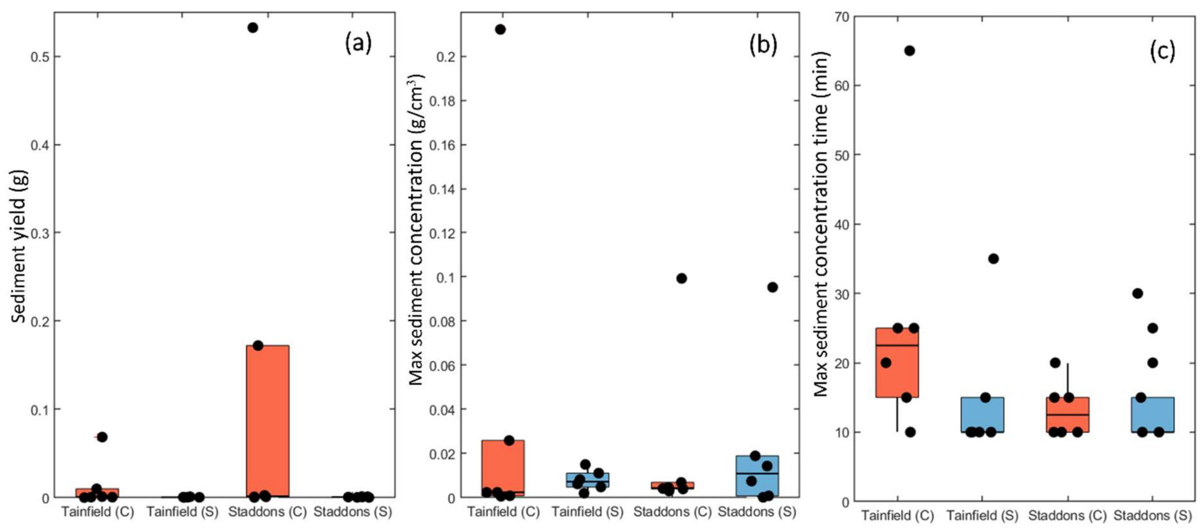

Figure 6.13. Box plots depicting total sediment yield for each simulation and metrics for generated suspended sediment data (scatter dot per simulation): maximum suspended sediment value and time of peak suspended sediment.

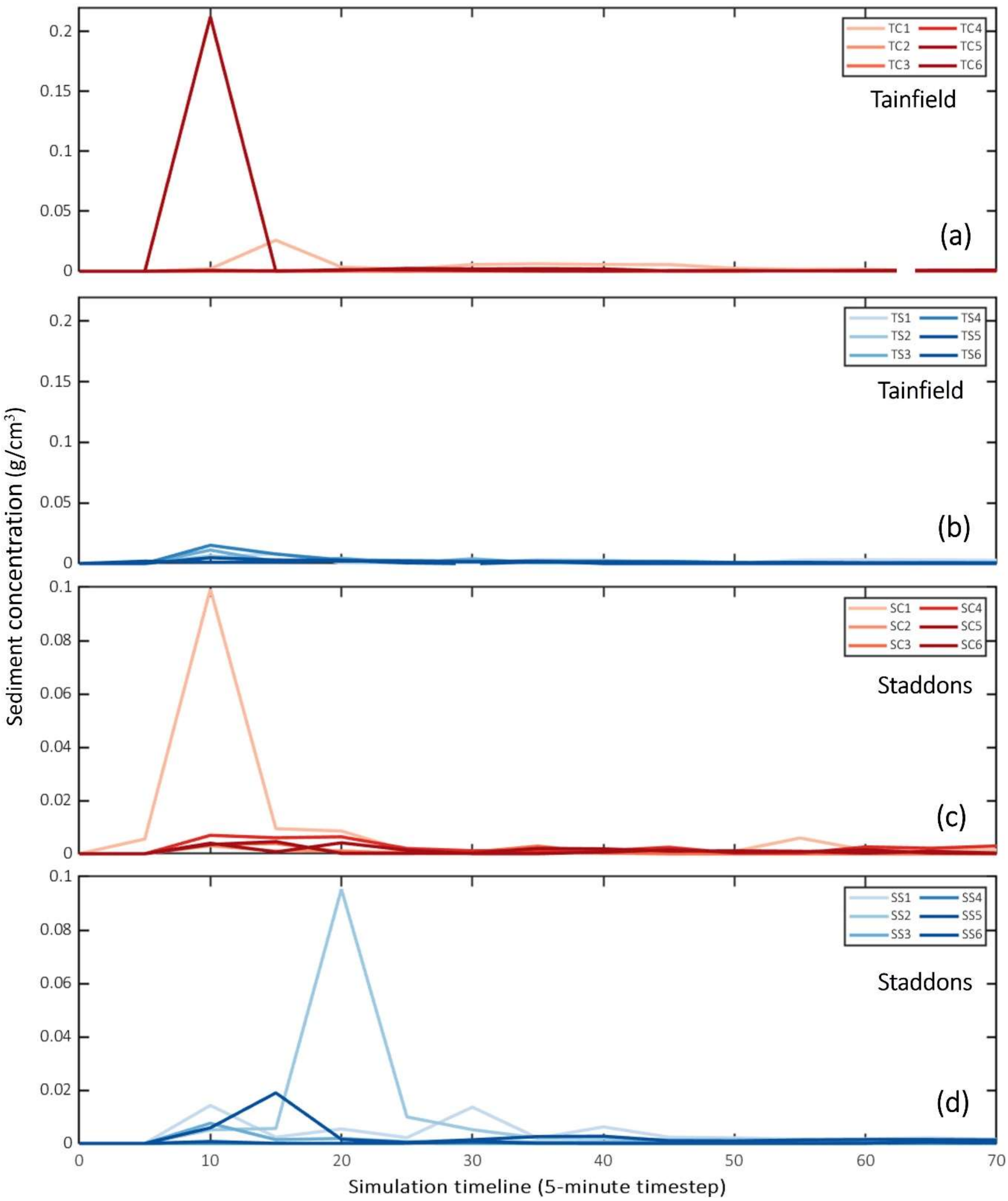

Figure 6.14. Sediment concentration for Tainfield and Staddons across a 5-minute timestep. Plotted are 6 simulations for each subsoiled/control and field site. Simulations are detailed as S (subsoiled) or C (control) and numbered 1-6.

6.5. Discussion

Results from this study have demonstrated the potential of subsoiling to improve the physical and hydrologic properties of soil, including runoff reduction. This trend is not uniform throughout however and the datasets produced illustrate the high spatial and temporal variability of these results.

6.5.1. Subsoiling improves soil physical properties

Overall, my results showed that subsoiling causes a reduction in compaction, illustrated through lower bulk density values at 4 of the 5 studied farms. The variable nature of these results is expected considering the value ranges presented in the literature, for example with bulk density increases and decreases under subsoiling across multiple years (Sojka *et al.*, 1993). In this study, median bulk density reductions ranged between -19.7% (Tainfield) and +4.75% (Newcotts). Immediately prior to sampling at Newcotts, the grassland crop had been cut. The recent heavy machinery traffic may be a contributing factor to the higher bulk density values recorded here.

Trends in the literature also show subsoiling to reduce bulk density values (eg. Evans *et al.*, 1996; Jin *et al.*, 2007; López-Fando, Dorado and Pardo, 2007; Feng *et al.*, 2018; Peralta, Alvarez and Taboada, 2021). However, it is important to stress that reductions in this study are relatively high compared to those elsewhere. Under subsoiling, Peralta, Alvarez and Taboada (2021) reported an average 4.3% reduction, Feng *et al.*, (2018) presented an average 6.3% reduction and Jin *et al.*, (2007) showed an average 4.9% reduction. In this study, reductions under subsoiling were up to 19.7% (Tainfield) and 16.87% (Staddons). These sites also presented the highest control compaction values (median of 1.39 and 2.2 g/cm^3 for Tainfield and Staddons, respectively). A contributing factor may be that the bulk density samples taken in this study were surface samples, whilst in the literature, samples up to 40cm deep have been taken, where reductions in compaction were considerably diminished with increasing soil depth (eg. Asenso et al., 2019; Feng et al., 2018; López-Fando et al., 2007; Peralta et al., 2021). Indeed, bulk density reductions under subsoiling were on average 8.6%

for surface cores, compared to 3.7% at 30-45cm depths in analysis by Feng *et al.*, (2018). Deeper cores were not possible in this study as all sites were located on working farm fields, with crops mid-growth.

On a similar note, higher soil organic carbon (SOC) values were presented under subsoiling, for four of five farms (three showing significant changes). The highest SOC values were also accompanied by the lowest bulk density values. This corresponds with the literature where subsoiling is attributed to small increases in SOC, for example <1% (Getahun *et al.*, 2018; He *et al.*, 2019a; Shukla *et al.*, 2020). These small increases may be attributed to the lower amount of tillage applied, where topsoil is conserved, there is a reduction of aggregate breakdown and aeration and thus lower rates of organic matter mineralisation (López-Fando *et al.*, 2007). These trends are associated with high variation, in the literature (eg. Borek, 2020; Zhang *et al.*, 2020) and in these results by up to 8% (Wellington, Control), highlighting the dominance of inter-field variation. Whilst in this study cores were taken to a 20cm depth, with the full sample used, in the literature there are minimal or negative impacts of subsoiling for SOC reported with depth increase (eg. López-Fando, Dorado and Pardo, 2007; He, Shi and Yu, 2019). Asenso *et al.* (2019) presented SOC increases of up to 13.68% at a 0-10cm depth, however for a 20-40cm depth, 27.12% reductions in SOC were extracted.

6.5.2. Subsoiling increases soil infiltration, based on single-ring infiltrometers

Results showed increases in soil infiltration under subsoiling, based on single-ring infiltration experiments at four of five sites. These trends are reflected in the literature, both through infiltration experiments (eg. Sojka *et al.*, 1993; Schwartz and Smith, 2016; Borek, 2020; Shukla *et al.*, 2020) and by inferring based on other data, for example from penetration resistance and soil moisture tests (Akinci *et al.*, 2004; Feng *et al.*, 2018).

The five sites demonstrated markedly different responses to infiltration rate change under subsoiling. Newcotts demonstrated very minimal change, which mirrors the small increase in bulk density reported here, suggesting for this site subsoiling had an overall minimal impact.

Frys demonstrated decreases in infiltration under subsoiling, although this was not significant. The minimal effect of subsoiling at these two sites may be accounted for by the 10-month gap between subsoiling and fieldwork for Newcotts and Frys. In the literature, the impacts of subsoiling have been found to be markedly reduced with time and between seasons (eg. Evans *et al.*, 1996). In addition, as previously noted, immediately prior to fieldwork at Newcotts the grass crop was harvested. The effects of harvesting machinery may have contributed to additional site compaction, accounting for the low infiltration rates here.

However, there were large increases in infiltration rates under the miscanthus subsoiled sites (Wellington, Tainfield and Staddons). In addition, Tainfield presented both the highest percentage reduction in both infiltration rate and bulk density. The variation in impacts from subsoiling on infiltration rate is highlighted in the literature (eg. Bormann and Klaassen, 2008; Peralta, Alvarez and Taboada, 2021). Indeed, some studies present very high increases in infiltration (eg. 50 times greater median infiltration rate (Schwartz and Smith, 2016) and 5 times greater rates (Peralta *et al.*, 2021). Elsewhere, minimal (eg. Curran Cournane *et al.*, 2011) or negative (eg. Franklin *et al.*, 2007) change is reported, in these cases for the effects of soil aeration, which reflects the results from Newcotts and Frys in this chapter, which show minimal and negative changes, respectively. These variations can be attributed to the range of land uses, soil types, previous management system, state of control and subsoiling quality and execution, including the depth and interval period (Raper and Bergtold, 2007; Wang *et al.*, 2020b; Lou *et al.*, 2021). In addition the impact of inter-field variability is expected to be high, for example depending whether infiltration tests are conducted in the beds or furrows of fields (Boulal *et al.*, 2011).

6.5.3. Subsoiled miscanthus crop produces lower overland flow under simulated heavy rainfall

The rainfall simulation results showed overall reductions in surface runoff under subsoiling albeit with high variation. These reductions were particularly marked for Staddons, where some simulations produced runoff coefficient values up to 39% higher than the highest recorded values under subsoiled plots. Comparisons of these trends with the literature is hindered by limited studies on subsoiling (Sone *et al.*, 2019), although there is research that has assessed the impact of other soil management practices on runoff, infiltration, and erosion, using rainfall simulation. These practices include reduced tillage (Dimanche and Hoogmoed, 2002; Boulal *et al.*, 2011; Laufer *et al.*, 2016), no tillage (Rhoton *et al.*, 2002; Engel *et al.*, 2009; Panachuki *et al.*, 2011; de Almeida *et al.*, 2018; Sone *et al.*, 2019), aeration (Franklin *et al.*, 2007), strip tillage (Truman *et al.*, 2007; Laufer *et al.*, 2016) and cover crops (Repullo-Ruibérriz de Torres *et al.*, 2018). These soil management methods, collectively aim to reduce runoff and improve infiltration, largely through improving soil structure and health.

Reductions in runoff by 55% and 92% under strip and reduced tillage respectively relative to a control were reported by Laufer *et al.*, (2016). Reductions in runoff by up to 26% were attributed to reduced tillage by Rhotonet al (2002) leading to higher infiltration rates as a result of earthworm activity, reduced surface residue and increases in organic carbon. Indeed, traditional tillage is associated with seal formation under rainfall, which promote higher surface runoff (Dimanche and Hoogmoed, 2002; Zhang *et al.*, 2010).

However, these trends are not uniform throughout the literature (Panachuki *et al.*, 2011). In this chapter, inter-field variation is very high, most notably for the controlled plots, where maximum runoff coefficient values varied between 2% and 52% across the 12 control simulations. The variation in the results produced in this chapter was most clearly reflected by the gradual pooling of rainfall across simulations and then sudden release of surface runoff. Omidvar et al., (2019) and Zhang *et al.* (2010) reported high variation in runoff, including once simulations had reached a steady state. Widely cited characteristics such as vegetation cover are attributed to being more significant at altering runoff than the soil management method (Engel *et al.*, 2009; Panachuki *et al.*, 2011; de Almeida *et al.*, 2018; Omidvar *et al.*, 2019). Results from Franklin *et al.*, (2007) showed both marked increases and decreases in surface runoff (eg. up to 35%), where under aeration, poorly drained soil increased runoff, whilst well drained soil decreased runoff. Finally, the role of antecedent conditions was highlighted in the literature as a potential key control (eg. Vermang *et al.*, 2009; Zhang *et al.*, 2010), although this was not identified as such in this study.

Other studies have concluded that improved soil structure had no or minimal impact on drainage, infiltration or runoff (Smit et al., 2016), for example as a result of aeration

(Logsdon and Sauer, 2017). Results from Sone *et al.*, (2019) showed higher surface runoff values under subsoiling, relative to a control, although this was unexpected and was attributed to the time between subsoiling and the rainfall simulations. This is reflected in certain simulations in this study where the range of runoff values produced across all tests reveal an overlap in runoff coefficients between controlled and subsoiled plots.

In this chapter, infiltration was measured using two methods: a single-ring infiltrometer and a rainfall simulator. Singled-ring experiments provide the advantage of the ease of executing a very high number of tests (280 conducted across this study) and high flexibility with deployment, for example they can be carried out in between dense crop. However, it is important to emphasise that infiltration values produced from single-ring infiltrometers are likely overestimated by the rapid wetting and ponding of a head of water above the ring, which can exacerbate surface seal formation (Lili *et al.*, 2008) and the small size of the ring which promotes edge effects. Furthermore, a standing head of water above the soil surface in an infiltration ring does not replicate rainfall event conditions and leads to overestimation of infiltration rates. Comparisons of infiltration rates produced by single-ring infiltrometers and a rainfall simulator in the literature, confirm the significantly higher infiltration rates produced by single-ring infiltrometers (Sidiras and Roth, 1987; Verbist *et al.*, 2013). This is also confirmed in this chapter where comparisons of infiltration rates using the two methods show single-ring infiltration rates to be up to an order of magnitude higher than rates produced by a rainfall simulator in the same field type. In addition, single-ring infiltrometers cover only a very small area, likely producing high field-scale variability (Boulal *et al.*, 2011). Therefore, the use of rainfall simulation provided useful outputs more comparable to real rainfall events than single-ring tests. In addition, the use of a rainfall simulator enabled the collection of erosion data (quantified here as suspended sediment and sediment yield), which as a key potentially wider benefit of NFM and one that is seen to be primarily driven through enhanced runoff, is a useful addition of knowledge to these results.

6.5.4. Subsoiled miscanthus crop demonstrates lower overall sediment yields in response to simulated heavy rainfall

Sediment yields were higher for control simulations relative to subsoiled plots, in line with the runoff coefficients. This is reflected in studies by Laufer et al., (2016) and Nolan et al., (1997) where far higher sediment concentrations were reported under intensive tillage simulations, relative to reduced, no and strip tillage plots. Engel et al., (2009) also reported higher sediment concentrations in the early minutes of controlled simulations, whilst no tillage plots were found to produce widely very low sediment concentrations. This was attributed to soil surface fragmentation and the subsequent detachment and transportation of soil particles following rainfall impact (Sojka *et al.*, 1993; Omidvar *et al.*, 2019). In this study, Staddons produced markedly higher sediment yield values, compared to Tainfield. This may be accounted for by the higher surface runoff at Staddons, although the greater crop density at Staddons would be expected to somewhat protect soils from initial rainfall impact due to the crop canopy (Engel *et al.*, 2009).

It is important to note that across all simulations, sediment yields, and the associated suspended sediment concentration values vary widely and in certain cases, controlled and subsoiled plots present very minimal differences. Minimal changes are also reflected in studies elsewhere, on account of the variation in results across the literature. For example, Nolan *et al.*, 1997; Logsdon, Kaspar and Cambardella, 1999; Omidvar, Hajizadeh and Ghasemieh, 2019 report soil management methods to have minimal impacts for erosion. High variation associated with suspended sediment values is also reported by Engel et al., (2009) and Zhang et al., (2010).

All simulations produced the highest suspended sediment values earlier on in the simulations. This pattern is seen in the literature where sediment concentrations are typically high soon after rainfall starts, for example Perkins & McDaniel, (2005) presented high values for the first 5-10 minutes of simulations, which reduced to a steady state. This pattern is also highlighted by (Zhang *et al.*, 2010), attributed to low runoff values alongside high initial rainfall impact and sediment detachment. With time, runoff rates rise, and sediment concentrations become more diluted. Thus sediment concentration and runoff are expected to reach steady state at a similar time on account of their close relationship (Zhang *et al.*, 2010; Omidvar *et al.*, 2019).

The detailed evidence from the literature provides useful context and comparisons for the results in this study. However it must be stressed that the literature is almost entirely reliant on international studies, with minimal evidence specific to UK catchments. However, these studies typically focus on soil management methods such as reduced or no tillage. Whilst these methods have a similar aim in soil structure improvements through machinery-based methods, they are ultimately different agricultural soil husbandry methods and are used in different contexts within an agricultural environment (eg. utilise particular equipment, soil types and available knowledge). Therefore, the evidence produced in this study aims to supplement prior research, firstly in a UK agricultural catchment, and secondly introducing subsoiling as an alternative soil management measure for NFM, where current applicable research is highly variable.

6.6. Conclusion

This study presents an examination of the use of subsoiling for Natural Flood Management, based on the impacts of soil management for physical and hydraulic soil properties and response to high magnitude simulated rainfall. Presented are empirical datasets for five sites in the Tone and Parrett catchments (SW-England), considering both inter-field and inter-site variability.

Utilising part-field trials occurring in the Tone and Parrett catchments, analysis here produced empirical evidence that subsoiling reduces compaction, improve soil organic carbon content, and increase infiltration rates. The use of a rainfall simulator at two miscanthus sites, illustrated the benefits of subsoiling for reducing overland flow and consequently overall sediment loss. Values produced were highly variable, with very high overland flow quantities not occurring for all simulations. This is expected due to the inherent variability of soils, even within the same field. Producing datasets such as these is vital in order to improve understanding of the potential benefits of subsoiling for Natural Flood Management and thus to consider these variables. Indeed, it cannot be assumed that singular values can be used to parameterise soil processes, such as, infiltration, because as demonstrated in this study, even within the same field, plot-scale simulations (as well as micro-scale single-ring infiltration tests), vary enormously.

Nevertheless, the potential benefits of improved agricultural management for NFM must be emphasised. Whilst soil management is widely seen as beneficial for soil structure and crop yield on a local scale, the potential improvements that appropriate management could make on a catchment scale could also be substantial. The collection of further datasets in the future, to include different land uses and catchments, as well as to consider the impact of time since subsoiling occurred (repeat sampling and testing) will be of particular benefit to develop the findings presented in this chapter.

6.7. Appendix

This appendix presents the empirical datasets used in this study: bulk density, soil organic carbon, and runoff, infiltration, suspended sediment, and sediment flux values from each rainfall simulation. For each table, N = Newcotts, F = Frys. W = Wellington, T = Tainfield and S = Staddons. In addition, (C) = control and (S) = subsoiled.

6.7.1. Bulk density

No.	NC	NS	FC	FS	WC	WS	TC	TS	SC	SS
1	1.23	1.19	1.21	0.99	1.18	0.95	1.17	1.64	1.30	1.20
2	1.24	1.32	1.26	1.36	1.52	1.03	1.90	1.73	1.39	0.98
3	1.33	0.97	1.43	0.98	1.21	0.94	2.00	1.75	1.33	1.13
4	0.85	1.01	1.41	0.79	1.26	0.89	2.27	1.46	1.54	1.41
5	0.96	1.12	0.92	1.39	1.37	1.04	2.00	1.63	1.49	1.07
6	0.82	1.32	1.19	1.16	1.20	1.14	2.09	1.77	1.55	1.15
7	0.99	1.17	1.44	0.93	0.98	1.15	1.84	1.84	1.20	1.05
8	1.13	1.01	1.26	1.16	0.98	1.08	1.82	1.71	1.39	1.19
9	1.06	1.32	1.10	1.19	1.24	0.75	1.22	1.74	1.51	1.15
10	1.10	0.84	1.18	0.87	0.87	1.00	2.05	1.82	1.22	1.03
11	1.12	1.26	1.21	0.95	1.09	0.71	1.97	1.62	1.74	1.22
12	1.34	1.12	1.40	1.26	1.02	0.85	1.95	1.67	1.48	0.92
13	1.05	1.11	1.46	1.28	1.16	0.87	1.88	1.62	1.39	1.23
14	1.19	1.15	1.14	1.08	1.07	0.94	2.01	1.54	1.37	1.54
15	1.21	1.35	1.33	1.09	1.19	1.05	2.08	1.64	1.27	1.02
16	1.20	1.13	1.29	1.20	1.23	0.90	1.84	1.69	1.31	1.03
17	1.08	1.08	1.28	1.16	1.08	0.88	1.97	1.70	1.38	1.15
18	0.84	1.21	1.12	1.26	0.88	1.03	2.04	1.47	1.28	0.94
19	1.01	1.17	1.18	1.30	0.80	0.59	2.15	1.56	1.32	1.41
20	1.25	1.16	1.33	1.49	1.10	0.94	2.22	1.44	1.38	0.94
21	1.03	1.12	0.98	0.93	0.81	1.14	2.02	1.57	1.38	1.37
22					0.81	1.08	1.94	1.49	1.34	1.37
23					0.76	0.86	2.10	1.58	1.39	1.49
24					0.99	1.13	2.20	1.50	1.43	1.31
25					0.82	0.63	2.05	1.62	1.56	1.22

26					1.10	1.15	2.21	1.50	1.53	1.10
27					0.95	0.90	1.91	1.69	1.40	1.47
28					0.94	0.73	1.99	1.53	1.40	1.52
29					0.82	1.04	2.15	1.54	1.44	1.24
30					1.44	1.08	2.22	1.42	1.54	1.10
31							1.94	1.62	1.53	1.15
32							2.11	1.70	1.34	1.21
33							2.15	1.58	1.38	1.22
34							2.09	1.78	1.32	1.15
35							1.82	1.01	1.21	0.95
36							2.14	2.02	1.46	1.14

6.7.2. Soil organic carbon

No.	NC	NS	FC	FS	WC	WS	TC	TS	SC	SS
1	7.59	8.65	3.6	4.48	5.91	3.54	4.53	2.15	4.38	4.69
2	8.9	7.43	3.97	4.36	6.68	3.54	4.77	2.73	4.87	4.59
3	8.34	7.63	4.38	3.99	6.13	3.48	4.83	2.77	4.51	4.81
4	9.21	7.61	3.74	4.77	5.58	3.41	4.97	4.33	4.35	5.07
5	8.47	6.19	3.79	4.49	5.16	3.81	4.01	4.36	4.49	5.00
6	8.82	6.74	3.72	4.03	5.63	3.54	4.17	4.27	4.57	5.02
7	9.3	7.12	4.43	3.17	5.64	4.18	4.32	3.78	5.52	4.59
8	8.88	6.91	3.52	3.37	4.95	4.44	4.67	3.39	5.46	4.57
9	8.29	6.66	3.72	3.91	8.56	3.41	4.69	3.67	5.50	4.63
10	8.66	7.37	3.99	3.59	5.16	3.23	4.12	3.59	3.79	4.62
11	8.52	7.65	3.42	3.4	5.48	3.77	4.07	3.63	3.62	3.73
12	8.46	7.91	3.19	3.05	5.53	3.74	4.29	3.56	3.65	4.95
13	9.1	7.48	3.13	3.02	5.11	3.59	6.01	4.40	3.73	4.14
14	7.19	7.91	3.64	3.82	4.89	3.57	6.07	4.17	3.81	3.99
15	7.78	8.77	3.51	3.05	5.07	4.93	6.14	4.23	3.58	4.18
16	9.14	7.93	3.47	4	6.15	4.65	3.71	3.89	3.43	4.32
17	9.32	7.52	3.72	4.71	4.79	3.96	3.61	4.13	3.29	4.20
18	9.52	7.03	3.81	4.54	4.72	4.02	3.71	4.14	3.35	4.16
19	8.92	7.12	3.7	4.1	5.63	4.52	4.23	3.54	4.74	5.41

20	9.5	7.84	4.19	3.91	5.47	4.08	4.22	3.56	4.87	5.63
21	9.13	7.09	3.72	3.92	5.68	3.88	4.91	3.34	5.03	5.52
22					5.60	3.81	4.08	4.56	4.43	5.49
23					4.87	4.03	3.91	3.68	4.49	5.09
24					4.51	3.92	4.08	4.73	4.50	5.52
25					4.07	3.13	2.96	3.71	4.88	5.41
26					3.98	3.13	3.95	3.85	5.01	5.60
27					5.13	3.77	3.91	3.74	5.24	5.50
28					5.00	3.80	3.72	3.46	5.33	5.06
29					7.32	3.99	3.80	3.29	5.37	5.02
30					6.87	3.89	3.49	3.75	5.33	5.28
31					5.91	5.51	3.95	3.72	5.46	4.44
32					5.71	4.06	3.59	3.71	5.81	4.41
33					5.57	4.56	3.44	3.72	5.48	4.50
34					5.48	5.08	3.51	4.17	4.42	5.41
35					3.96	4.81	3.45	4.18	4.44	5.46
36					4.15	4.50	3.80	4.32	4.53	5.31
37					5.29	6.01				
38					5.18	6.24				
39					3.43	5.43				
40					3.47	5.28				
41					3.81	4.89				
42					4.46	4.69				
43					3.36	5.27				
44					3.39	5.30				
45					3.81	5.41				
46					3.79	5.21				
47					3.53	5.03				
48					3.49	3.71				
49					3.70	4.49				
50					3.76	4.57				
51					3.22	4.72				
52					3.05	6.09				
53					6.59	5.08				
54					6.58	5.08				
55					3.57	6.63				
56					5.70	10.33				

57	6.54	4.73
58	6.56	2.42
59	4.86	7.38
60	4.36	6.94

6.7.3. Single-ring infiltration rate

Values are presented in mm/hr for mean infiltration (steady state)

No.	NC	NS	FC	FS	WC	WS	TC	TS	SC	SS
1	15.41	66.76	566.29	338.91	63.12	42.35	58.80	127.79	1.60	81.79
2	15.41	56.49	323.51	182.67	151.75	88.99	7.99	78.83	54.46	34.40
3	66.76	20.54	138.65	308.10	107.49	68.46	93.16	722.32	28.75	105.06
4	82.16	261.89	611.07	580.26	4.81	105.05	139.53	340.62	11.49	38.34
5	15.41	30.81	379.99	97.57	91.72	54.84	138.98	541.23	33.68	238.94
6	46.22	15.41	549.45	347.08	35.14	165.33	164.15	581.43	83.12	298.10
7	56.49	27.40	498.10	749.72	28.87	89.35	13.31	156.36	99.03	482.40
8	41.08	46.22	347.08	128.38	6.52	46.15	17.91	194.25	18.06	503.95
9	118.11	10.27	785.66	1004.7	7.17	7.17	60.14	336.80	36.88	38.49
10	107.84	169.46	51.35	872.96	8.02	2.28	138.44	255.57	48.73	212.11
11	18.27	109.60	395.40	138.65	3.99	14.33	34.47	291.86	54.31	416.95
12	92.43	25.68	420.15	179.73	179.18	134.38	17.20	718.99	1.64	44.73
13	45.67	107.84	729.18	264.88	10.75	47.92	64.02	272.30	6.41	522.79
14	102.70	107.84	313.24	195.13	4.07	35.83	57.33	26.73	31.95	28.66
15	30.81	27.40	195.13	549.45	71.88	105.88	34.61	51.98	13.13	13.13
16					4.65	109.09	17.37	622.96	11.47	12.78
17					2.29	11.20	3.99	231.61	28.75	156.54
18					9.58	9.18	3.58	182.42	14.33	117.52
19					24.15	6.41	10.26	42.10	9.62	80.44
20					1.29	41.15	20.05	85.99	8.21	176.40
21					18.51	12.83				
22					0.29	36.45				
23					15.97	44.27				
24					121.82	63.06				
25					48.87	48.97				

26	197.78	115.38
27	52.12	23.25
28	58.64	223.63
29	22.40	6.41
30	41.53	143.76
31	6.41	47.47
32	2.87	22.93
33	9.62	74.93
34	43.98	62.19
35	25.56	7.51
36	48.73	56.38

7. Conclusions, synthesis, and recommendations

7.1. Introduction

This thesis aims to assess the function and efficacy of Natural Flood Management measures, according to key hydrological properties: to slow and attenuate channel flow, reduce field runoff, and increase soil infiltration, with particular consideration to the role and impact of NFM design structure and management. This chapter will bring together the results and empirical datasets produced in this thesis, that were introduced in chapter 2 and detailed and analysed in chapters 3-6 to summarise how this aim has been achieved.

Firstly, the key scientific contributions of this thesis will be outlined, followed by a brief examination of the applicability of the produced datasets. Next, the results of this thesis will be synthesised within the context of available NFM datasets within the literature, by highlighting comparisons and drawing on common themes and similarities. This will highlight where the results produced in this thesis fit in within the wider UK NFM evidence base and the knowledge gaps our results have filled. Finally, areas for recommendation further study will be detailed.

7.2. Scientific contribution

Land use changes, landscape modifications and changing climate have resulted in local to regional flood risk increases in recent decades. As an alternative to traditional engineering approaches, there has been a movement towards catchment-based flood risk management, a subset of which is NFM. NFM aims to enhance flood resilience through the slowing and storing of runoff and flow, based on the restoration and augmentation of hydrological and morphological catchment features. The introduction and application of NFM in the UK in recent years has become increasingly widespread, however confidence and further expansion is constrained by limited evidence to quantify and assess the impact that NFM may have in the landscape (Barlow *et al.*, 2014a; Wingfield *et al.*, 2019; Monger *et al.*, 2021). This thesis has addressed this challenge by producing a series of empirical datasets for the Tone and Parrett catchments in SW-England. These datasets present key hydrological properties associated with NFM measures, principally: channel flow, channel volume storage, soil infiltration, and field overland flow that are used to assess their role, function, and impact in response to rainfall events. From extensive analysis of these datasets, key recommendations for NFM structural design and adjustments are made, along with an assessment of NFM management and maintenance requirements, applicability, and successful execution.

The key scientific contributions of this thesis are:

1. An improved understanding of the controls on the function and efficacy of NFM measures, including structural designs, event rainfall and antecedent conditions.
2. A new comprehensive event definition methodology for the extraction of rainfall events according to channel flow and pond volume.
3. A compilation of NFM empirical datasets for the Tone and Parrett headwater catchments (SW-England), that quantify key hydrographical properties impacted by NFM measures. All empirical datasets produced and analysed in this thesis will be made available via the University of Bristol open access repository.
4. An assessment of the response of NFM measures to a range of rainfall events, including both low flows and high magnitude filling events, with consideration to the impacts produced across the full hydrograph. Findings showed marked peak flow reductions downstream of offline water storage ponds and leaky woody dams during the largest recorded events.
5. A range of structural design recommendations for future NFM construction and management, based on empirical evidence.
6. An examination of the role and impact of management and maintenance tasks showed that marked pond management occurred throughout the monitoring period, where key tasks were deemed typically feasible, applicable, and effective for maximising pond function.
7. First small plot-scale assessment of the impacts of subsoiling for NFM in a European catchment, demonstrating infiltration increases and overland flow decreases under subsoiling 1m^2 rainfall simulation plots, alongside marked inter-field variability.

7.3. Applicability of the produced empirical datasets

The empirical datasets produced from this thesis will be applicable for a variety of purposes. Firstly, to inform local NFM structural decision making, for instance based on the impacts of the features monitored and the attributes that worked well or where recommendations were made. This may be beneficial for FWAG-SW who implemented all the studied NFM measures or NFM practitioners elsewhere who are seeking advice and knowledge on design and expected impacts. In addition, this information may be used by landowners and farmers where NFM features have been deployed or constructed to highlight the impact of their cooperation and efforts and to maintain local engagement. Community cooperation has been widely confirmed to be essential for NFM uptake and sustainability (Howgate and Kenyon, 2008; Mehring *et al.*, 2018; Garvey and Paavola, 2021) and thus the production of real-world, observational values and analysis is essential to inform and support new NFM proposals. Finally, these datasets may be used as observational data for future modelling applications, where the impacts of NFM at the local scale (as analysed in this thesis) can be upscaled to consider catchment-scale flood risk. The use of observational datasets in models may be used to characterise individual NFM features (based on their learnt behaviours from empirical data observations) or to compare model projections with real-world values, also allowing for greater consideration of model uncertainties (than if no observational datasets were used).

It is also important to ensure transparency of the produced results, to highlight the timescales over which this data may be applicable. The datasets and results produced from storage pond sites (Halsewater, Merriott and Wellhams) can be viewed as relatively static and could feasibly be used as results for the respective sites in comparable conditions in the future. For example, if identical event input conditions (eg. event rainfall intensity and duration and antecedent conditions) occurred again in 2022, the impact of ponds on downstream flow may be expected to produce similar values. This is reflected by the key controls for pond filling (eg, recorded inlet heights) which are not expected to significantly change over time without alteration. However, results from leaky woody dam sites (Marcombe Lake), should be viewed as a snapshot of NFM impacts from newly deployed features due to their expected dynamic evolution within the channel across events and between seasons as accumulating debris and channel morphology change (Sear *et al.*, 2010; Thomas and Nisbet, 2012).

Furthermore, it is important to highlight the challenges of widespread implementation of different NFM measures. As an example, agricultural management methods to improve soil structure (eg. subsoiling, as measured in this thesis) could feasibly be conducted widely across a catchment. Indeed, the subsoiling trials monitored in chapter 6 all occurred on land that is actively farmed for crop production. In contrast, the river-channel based structures monitored in this thesis all rely on dedicated areas of farmland for their construction, which is limited to a relatively small number of locations where they could be designed. Key location requirements are that they need to be installed adjacent or within a river channel and in the case of the sites monitored in this thesis are all located on farmland that is not used for agricultural purposes by the landowner. Future Environmental Land Management policies that are currently being introduced in the UK may have the potential to make a marked impact on the spatial distribution of NFM measures. Through new incentivisation for farmers and landowners to designate large areas of land for enhancing ecosystem services (eg. whole habitat restoration and land use change under ‘Landscape Recovery’, see DEFRA, 2021b), it may be more desirable for landowners to dedicate larger areas of farmland for NFM in the future (or more widely under NBS), and not solely in locations that aren’t being used for agricultural production.

7.4. Synthesis

This following section will highlight how the key scientific contributions of each research chapter complement and enhance previous research. It will place the empirical datasets and analysis presented in this thesis into a wider, UK-based NFM context through comparisons with key NFM studies, according to the overarching aim of this thesis: to assess the function and efficacy of Natural Flood Management measures. This will be conducted by examining the key hydrological properties assessed at various NFM sites in this thesis: to slow and attenuate channel flow, reduce field runoff, and increase soil infiltration in the context of the key literature.

7.4.1. Offline water storage ponds (chapter 3)

Chapter 3 examined the efficacy of two contrasting designs of offline water storage pond to attenuate downstream flow across a range of rainfall events. Whilst this was the first analysis of constructed offline water storage ponds for NFM that could be identified in headwater catchments in South-West England, relevant studies with empirical data collection are located in the Belford catchment (eg. Wilkinson *et al.*, 2010a, 2010b; Nicholson *et al.*, 2012, 2019), Evenlode catchment (Robotham *et al.*, 2021) and Eddleston catchment (Black *et al.*, 2021). These new studies have also focused on the wider benefits of ponds for sediment and nutrient retention, and combined impact of a range of NFM features (including ponds) for flow lag times, up to the catchment scale. There are also a number of large-scale NFM monitoring projects currently underway in UK catchments, where the production and publication of new datasets are expected in the coming few years, eg. Q-NFM (Hankin *et al.*, 2020; Page *et al.*, 2020).

Chapter 3 firstly examined the impact of offline water storage ponds on attenuating stormwater by analysing the hydrological conditions and structure required for effective pond function. The two studied offline water storage ponds highlighted the discrepancies in pond structure and design, even within the same wider project scheme (Hills to Levels). Whilst the two sites presented similar aims in terms of their response to rainfall events: to fill, store and spill flow, directly from the river channel during high flow events, their impact on downstream flow was markedly different. Halsewater produced a greater quantity (5) of direct filling events, compared to Merriott (1), which was attributed to a more suitable pond structure at this site, which pond inlet and outlet heights were better suited to the experienced high flows. It is challenging to compare this proportion of direct filling events with those comparable sites identified in the current literature as in studies elsewhere it is typical for analysis to focus on a select, few events (eg. Nicholson *et al.*, 2019), through in-depth storm analysis, rather than presenting a full range of monitored events. Thus, a key contribution of chapter 3 is that it presents a full range of rainfall events for analysis, highlighting the structural and rainfall conditions required for offline storage ponds to function as designed. The systematic extraction of all captured events has been conducted elsewhere, for instance for study of beaver dams (eg. Puttock *et al.*, 2017), but not for NFM storage ponds. This is an important consideration to inform practitioners on future NFM design and how adjustments may be an optimal step following installations to maximise the potential use of NFM measures. For example, for Merriott, recommendations have been made to lower pond inlet heights to ensure pond filling directly from the channel during high flow events. These recommendations are particularly important for sites such as Halsewater and Merriott, which are largely unmanaged as their function (filling, storing, and filling) occurs naturally. Thus, this brings to attention practical considerations that may otherwise have been unnoticed.

Comparing pond designs and structures between these two sites and those for other offline pond sites in the literature is complex as whilst there are sets of design recommendations and knowledge available (eg. SEPA, 2015; Burgess-Gamble *et al.*, 2018), the natural context that all NFM measures are built around means that there is no definitive, standard framework for their construction. Moreover, it is clear that a structure that works well for one site, may need substantial adjustments and alterations at another site. For instance, at Halsewater, pond spillage took up to 7 days to occur following the largest recorded events. In contrast at offline ponds in the Belford catchment, adjustments were made following monitoring to increase drainage time to 5-6 hours (Wilkinson *et al.*, 2010b; Nicholson *et al.*, 2012).

The second key part of chapter 3 assessed the impact of ponds for downstream flow, in response to rainfall events. The responses seen by ponds at Halsewater and Merriott were notably different to comparable NFM features in the Belford catchment. Firstly, in the results here, the greatest percentage flow reductions (up to 7%) were recorded during the largest-magnitude events as it was during these that direct filling from the channel occurred. In contrast, in Nicholson *et al.*, (2019), smaller events produced peak flow reduction by up to 12%, whilst in larger events, pond storage capacities were reached before the event peak, lowering the overall pond impact. The issue of capacity exceedance prior to the event peak is one that has been intensively stressed within the relatively few studies on offline water storage ponds for NFM (Wilkinson *et al.*, 2010b, 2019; Nicholson *et al.*, 2012). This has further been considered with regard to the expectation that constructed ponds may silt up over time, reducing their overall storage capacity (eg. see Quinn *et al.*, 2013; Robotham *et al.*, 2021). For Merriott, the opposite side of this issue was presented, where for the upstream pond studied, inlets were not high enough to generate any direct filling during any rainfall events. Furthermore, for Merriott's one inlet filling event at the downstream pond, pond capacity was not reached until after the event peak. For Halsewater, no event monitored resulted in capacity being reached (across both ponds), despite 5 inlet-filling events occurring, during a relatively high rainfall winter period (2019/20).

Therefore, a marked contribution of chapter 3 to our knowledge of offline water storage ponds for NFM is that these structures reduce downstream peak flows during rainfall events. This attenuation effect is greatest during the largest magnitude events, although this efficacy is strongly dependent on the design of the pond, which must allow for direct filling from the channel during high flow periods. The results also highlight that regular pond volumes (as found at both ponds at Halsewater, and the upstream pond at Merriott), do not necessarily limit the efficacy of ponds in terms of potential storm capacity.

7.4.2. Leaky woody dams (chapter 4)

Chapter 4 presents new empirical datasets that have analysed the impact of newly deployed leaky woody dams in two stretches of river channel, through comparisons with upstream control sections. This is an important addition to the NFM evidence base on leaky woody dams, which is currently reliant on knowledge that has been gained in a small number of catchments and that largely utilises modelling methods. Whilst larger quantities of observational data are available that has assessed the impacts of naturally occurring in-channel wood, using this information to directly infer the impacts of deploying artificial in-channel wood is associated with large complexities. Indeed, artificially deployed leaky woody dams although aim to emulate naturally occurring in-channel wood, in reality have a different structure and expected behaviour, for instance may be secured in place and be deployed in unwooded or heavily modified river channels.

Overall, the results from Marcombe Lake in this thesis compliment prior findings in the literature. As with the offline water storage ponds studied in the chapter 3, no studies were found that had assessed the impacts of leaky woody dams in SW-England catchments, with the exception of studies on beaver dams, which will be considered separately. Studies were identified that have produced empirical datasets in the Stroud River Frome (Short *et al.*, 2019), Eddleston (Black *et al.*, 2021), Dane (Deane *et al.*, 2021) River Fenni (Thomas and Nisbet, 2012) and in non-UK catchments: the Schwarze Pockau, Germany (Wenzel *et al.*, 2014). Additional studies have established lab experiments to develop our understanding of leaky woody dam behaviour and impacts (eg. Muhawenimana *et al.*, 2021; Müller *et al.*, 2021a, 2021b). There are also a number of studies that have applied modelling methods to simulate the behaviour and impacts of leaky woody dams, in the Lymington River catchment (Dixon *et al.*, 2016) and Pickering Beck catchment (Odoni and Lane, 2010).

Chapter 4 examines the impact of leaky woody dams on channel flow by comparing peak flow upstream and downstream of measures. The greatest peak flow reductions were found during the largest magnitude events (categorised according to flow rise from event start to event peak), where reductions of up to 56% occurred downstream of leaky woody dams, compared to upstream. Comparing the values produced in chapter 4 directly with empirical datasets in the literature is complex as firstly, the majority of empirical literature on leaky woody dams focusses on the impact of naturally-occurring wood (eg. Gregory *et al.*, 1985; Mazzorana *et al.*, 2011; Deonie *et al.*, 2014). Secondly, this chapter has focussed on the impact of leaky woody dams on downstream flow, whilst previous works have analysed the impact on lag times (Black *et al.*, 2021), stage height (Short *et al.*, 2019) or the wider benefits of dams, such as for macroinvertebrate diversity (Deane *et al.*, 2021). However, it is important to stress that across all studies, the general consensus suggests that leaky woody dams present the potential ability to attenuate flow as a result of reductions in average stage height (eg. following NFM deployment from 0.252 to 0.204m by Short *et al.*, (2019) and increases in lag time (eg. between 2.6 to 7.3 hours at the catchment scale, by Black *et al.*, (2021).

Studies that were identified to assess the impact of leaky woody dams on peak flow were Wenzel *et al.*, (2014) which demonstrated average peak flow reductions under leaky woody dams of 2.2%. This study used artificial flow events (controlled water release from upstream), and as a result the findings showed only very small amounts of variation. This is a contrast from the results produced in this thesis, which showed marked variation in peak flow changes upstream to downstream of leaky woody dams, which for Upper Marcombe Lake were between a 0.06m^3/s (64%) increase and 0.14m^3/s (49%) decrease). This level of variation is consistent with results by Norbury *et al.*, (2021) depicted percentage changes downstream of leaky woody dams following installation of between a 124% increase and 11.4% decrease. The study by Norbury *et al.*, (2021) represents a particularly interesting comparison to the results gained in this thesis, as it presents a number of the same storm events as analysed in chapter 4 (including notably Storms Ciara and Dennis in February 2020, but for a headwater catchment in NW-England. Indeed, Norbury *et al.*, (2021) presented an average peak flow reduction of 27.3% downstream of leaky woody dams; comparable to results from chapter 4 which showed a marked mean peak flow reduction of 22% for Upper Marcombe Lake across all events in chapter 4.

The results from chapter 4 are also comparable to ongoing work that is assessing the hydrological impact of beaver reintroduction, although any comparisons should ultimately acknowledge the differences in structure and function of beaver dams and artificially deployed leaky woody dams. Results by Puttock *et al.*, (2021) show far higher average peak flow reductions downstream of beaver dams than those shown by leaky woody dams in chapter 4, with mean values of up to a 60% reduction, compared to mean percentage peak flow reduction of 6% for Lower Marcombe Lake and 21% for Upper Marcombe Lake. However, notably for both leaky woody dams and beaver dams, peak flow attenuation was largest for the largest recorded events.

Therefore, chapter 4 makes an important contribution to the NFM empirical evidence base by presenting new datasets that have examined the impact of newly deployed leaky woody dams on downstream flow. This importantly builds on current empirical datasets specific to artificially deployed leaky woody dams (Wenzel *et al.*, 2014; Short *et al.*, 2019; Black *et al.*, 2021) and also compliments current research on the impacts of beaver dams for event flows (Nyssen *et al.*, 2013; Puttock *et al.*, 2017, 2021), but examines a full range of natural rainfall event responses, and the impact of leaky woody dams for peak flow.

7.4.3. Online water storage ponds (chapter 5)

Chapter 5 has produced the first study of an online water storage pond site for NFM, including an examination of the role, design, function, and impact of controlled, in-channel storage. Importantly, this chapter also made a critical evaluation of the role and success of pond management, including the importance and requirements of NFM site maintenance according to a series of defined tasks. Therefore, this chapter makes a new addition to the NFM evidence base as to date, online water storage ponds for NFM have remained relatively unclassified within flood management reviews.

In chapter 5, the close management of Wellhams ponds by a local flood warden group (an example of a CFG) resolved 5 individual maintenance issues over the 26-month monitoring period. This chapter also presented an assessment of the conducted pond management at the site, which highlighted the feasibility and appropriateness of tasks for maintaining and maximising pond function. This presented important recommendations for the management of similar sites elsewhere, an area of particular contribution as no previous studies could be identified that has assessed the role and impact of NFM management and maintenance directly within the literature. This chapter confirms prior observations and reports that have highlighted the importance of stakeholder engagement and utilising a bottom-up approach for NFM success (eg. Howgate and Kenyon, 2009; Mehring *et al.*, 2018; D'Souza *et al.*, 2021). In addition, this chapter develops discussions of management and maintenance issues and resolutions that are increasingly noted within NFM analysis. For example, Robotham *et al.*, (2021) highlighted the potential need for pond de-silting in the future as a reduction in storage capacity of up to 10% per year was reported for retention ponds. Issues of NFM storage capacities being reached are widely shared within the NFM empirical evidence base (eg. Evrard *et al.*, 2008; Barber and Quinn, 2012; Wilkinson *et al.*, 2019). Whilst this was not an issue at Wellhams during the monitoring period, the reassurance that a dedicated CFG offers a NFM sites means that there is greater security regarding potential future maintenance issues (compared to sites that are not directly or regularly managed).

Moreover, throughout the monitoring period, Wellhams (online) has relied upon regular (weekly- monthly depending on the season and rainfall forecasts) visits by a local flood warden team to ensure the pond function is maintained. Without these visits, pond function cannot be maximised (eg. to open and close the outflows based on seasons and rainfall events), and the faults that occurred would not have been fixed, which would likely have continued to have negative local impacts (flooding farmland), for instance on account of outflow blockage. As a result of this active and regular management at Wellhams, few recommendations for site design were necessary from the outcomes of this thesis, for example, all issues identified during the monitoring period, such as pond capacities being reached during the largest recorded events, were soon responded to through structural adjustments (eg. construction of additional, higher overflow pipes). This is a key contrast to our study of offline water storage ponds, where for Halsewater and Merriott (unmanaged sites) where a series of adjustments were proposed. Therefore, Wellhams perhaps presents an optimal example of NFM site management, although one that is perhaps unrealistic to occur at all deployed NFM measures, for example in terms of constraints with human capital, time, and funding.

Chapter 5 also introduces results that depict the impact of online storage ponds for flow storage during a range of rainfall events. This does not yet make the key step to measuring system inflow and outflow for analysis of the impact of ponds for flow reduction downstream (as in chapters 3 and 4). However, the pond volume dataset presented in this chapter introduces for the first time in the NFM evidence base, empirical data specific to this design of online storage pond. Key aspects of interest include the impact of outflow management on pond during rainfall events, which typically presents a far more marked control that the event rainfall input. Considering one of the largest recorded events in detail in this chapter demonstrated the potential delaying impact of constructing two in-channel ponds, separated by an outflow sluice, where the time to peak volume in the downstream pond was 2.25 hours longer than the time to peak volume in the upstream pond. This was despite the larger total volume capacity in the upstream pond, where thus a longer fill time is not unlikely, despite its upstream location. Comparing the event pond volume data presented here with the literature is challenging as no studies were identified that contained any comparable sites or structures. Within chapter 5, which is a contrast to chapter 3 and 4 which are building on current (albeit small quantities) empirical datasets within the NFM literature. This represents a key contribution of this chapter as it introduces online water storage ponds within an NFM context for the first time. It is widely accepted that a large variety of NFM features, distributed alongside more traditional, technical flood management (TFM) is likely to present the most optimal and realistic future flood management scenario for the UK (Kay *et al.*, 2019; Ellis *et al.*, 2021; Muhawenimana *et al.*, 2021). Thus, the consideration of all possible NFM measures, including those that present more characteristics of hard engineering features than other NFM types is of high importance to fuel the growth of the NFM empirical evidence base.

7.4.4. Subsoiling as an agricultural management method (chapter 6)

Chapter 6 presents the first UK plot-scale datasets that have examined the potential role and impact of subsoiling as an agricultural management method for NFM, based on key hydrological parameters to increase infiltration and reduce overland flow, along with the potential wider implications for sediment yield reductions. This makes an important contribution to the UK NFM evidence base as within the current literature the role of agricultural management methods for NFM is largely dependent on assumptions based on studies that have considered the impact of agricultural management for improving crop yields, based on soil physical properties, with the majority located in non-UK based catchments. The production of extensive sets of observed data that have quantified key hydrological parameters is important to gain a range of values that can encompass the range of catchment types within the UK. This will enable the development of future soil hydraulic model parameterisation and the assessment of land use and agricultural changes under NFM for flood risk reduction downstream within multiple different catchments.

Overall, the results from chapter 6 compliment and expand prior findings in the literature. Palmer and Smith's (2013) study was pivotal in the rationale for this chapter, on account of the widely identified overland flow, attributed to a widespread compacted and degraded soil structure across identified catchments in SW-England. Analysing the results of chapter 6 in the context of the literature is complex firstly as initially there appears to be a very large volume of literature that can be used to infer the benefits that subsoiling as an agricultural management method might have for reducing overland flow, increasing infiltration and as a result reduce catchment flood risk, for instance based on the study of physical soil properties (eg. as reviewed by Ngai *et al.*, 2017). However, within the literature to date, the focus and rationale of studies has been on the potential for subsoiling to improve crop yields, rather than as a flood management strategy. Furthermore, the few current empirical datasets that have been produced to assess the impact of subsoiling for key hydrological parameters (eg. infiltration and overland flow) are in non-UK based catchments and do not present comparable catchment conditions to the SW-England headwaters examined here (Sojka *et al.*, 1993; Truman *et al.*, 2005; Sone *et al.*, 2019; Borek, 2020). For example Truman *et al.*, (2005) examined tillage practices in the coastal plain soils in Georgia, where directly transferring results and values to catchments in SW-England (for example, in future upscaling and modelling applications) would introduce a number of assumptions. Within UK catchments, a small number of applications have assessed alternative agricultural management methods, including aeration, reduced, no and strip tillage in the upper Wye headwater (Deasy *et al.*, 2009), Loddington (Deasy *et al.*, 2014) and Hampshire-Avon (Withers *et al.*, 2007). Whilst these are comparable to the results of chapter 6 in the sense that all of these measures aim to reduce soil compaction, the methods associated with subsoiling differ in that machinery is used to target compaction deep into the subsoil.

Chapter 6 firstly produces and examines the impact of subsoiling for physical soil properties. This information compliments the current literature where the majority of current studies that have measured bulk density under subsoiling report percentage decreases, for instance by 4.3% (Peralta *et al.*, 2021), 6.3% (Feng *et al.*, 2018) and 4.9% (Jin *et al.*, 2007). Reductions in chapter 6 under subsoiling were up to 19.7%, although this may be attributed to the surface bulk density samples taken here. On a similar note, results in chapter 6 also depict overall increases in soil organic carbon under subsoiling, by up to 19% (Newcotts). There is high variation of relatable measurements in the literature, where some reports show very marginal increases in SOC under subsoiling (eg. <1%, He *et al.*, 2019; Shukla *et al.*, 2020), whilst others show larger changes of up to 13.7% between a 0-20cm soil depth (Asenso *et al.*, 2019). Contributions of chapter 6 to the existing evidence base that has assessed the impact of subsoiling for physical soil properties by presenting datasets specific to SW-England catchments, as well as presenting analysis based on a high sample number. For example, in the studies cited here, sample number sizes are typically between 2 and 6 per plot or field type or is not reported. In chapter 6, sample numbers were up to 36 per field type for bulk density and SOC, which was deemed highly important for a transparent analysis and consideration of the inter-field variation, which was deemed very high. Consideration of the variation in values is important for there to be confidence in their future application (eg. for soil parameterisation).

Chapter 6 also assesses the impact of subsoiling on infiltration and overland flow, based on two key methods: single-ring infiltration tests and a rainfall simulator. Whilst rainfall simulations offer small plot-scale measurements of overland flow in response to relatively realistic rainfall, single-ring infiltration tests allow for a high sample number and ease of deployment. Two key studies were identified that had used a rainfall simulator to examine the impact of subsoiling for infiltration or overland flow (Truman *et al.*, 2005; Sone *et al.*, 2019), both located in catchments outside of Europe. However, they presented markedly different results, where Sone *et al.*, (2019) presented decreases in mean infiltration rate of 24% (under vegetation) and 42% (under bare soil) as a result of subsoiling. In contrast, simulations by Truman *et al.*, (2005) showed subsoiling to increase infiltration by up to 26%. This level of variation was not unexpected and is illustrated in the results of chapter 6 which show high variation between plot types, although an overall increase in infiltration under subsoiling is reported, by a mean of 15.4% (Tainfield) and 14.6% (Staddons). A key response of chapter 6 to reported variation is to conduct a higher number of simulations, where 6 per field type were conducted, compared to 3 and 4 for Sone *et al.*, (2019) and Truman *et al.*, (2005), respectively. In addition, chapter 6 presents rainfall simulation findings depicting the impact of subsoiling for a UK catchment, which to date was not identified elsewhere. Furthermore, the potential wider benefits of subsoiling for reducing sediment yield are also briefly examined in chapter 6, from the analysis of suspended sediment samples, also collected during rainfall simulations. Whilst these findings do not directly contribute to the datasets of hydrological parameters (eg. infiltration and overland flow) produced in chapter 6, values of sediment yield are directly linked to the production of overland flow and so should be acknowledged and considered to ensure the transparency of analysis.

7.4.5. Summary

In summary, the empirical evidence generated in this thesis details the impact of a range of NFM features to recorded and simulated rainfall. Particular focus is given to their function, in terms of their design, structure, management, maintenance and thus overall potential and ability to slow, store or attenuate flow. In this thesis, the presented analysis has been split into four empirical chapters to reflect the individual function, behaviours, and impact of differing NFM structures and features. However, it is also important to highlight the common themes between the empirical datasets, as in practice, the key ideas and outcomes of this research are intrinsically linked through the overall contribution of this work to the UK and international NFM empirical evidence base.

The outputs from all four research chapters present results showing the impact of NFM features on flow storage, by peak flow reduction immediately downstream (chapters 3 and 4), overall pond volume (chapter 5) and overland flow (chapter 6). For all chapters, the potential benefits of NFM are shown through reductions or slowing of flow, particularly in response to large events, which are monitored (chapters 3-5) or simulated (chapter 6). Exploring key hydrological parameters throughout this thesis, but in the context of differing NFM features has enabled an examination of the immediate function or impact of each measure, for example, on downstream flow (for storage ponds and leaky woody dams), or overland flow (for hillslope-based soil management techniques). It has been widely suggested that a combination of different types of NFM features, distributed widely across the catchment may present the most effective scenario for flood management schemes (Ellis et al., 2021; Kay et al., 2019; Norbury et al., 2021), and thus it is important to build datasets that characterise the behaviour and impact of a range of NFM types across a catchment, which in this thesis has been within the Tone and Parrett catchments.

A common theme present throughout the results of all four chapters is that of variability, where NFM impact has been shown to depend on numerous factors including event conditions and magnitude, NFM structural design, management, and wider catchment characteristics. For example, the variability of soil characteristics and structure even at the field scale were likely key causes of the high variability present in the produced infiltration and overland flow values under both subsoiled and controlled plots in chapter 6. Whilst an overall impact could be identified, for instance that subsoiling overall may reduce overland flow, it was also clear that the ranges in values can be larger than the differences identified between subsoiled and controlled plots. This highlights the importance of the current expansion of the NFM empirical evidence base, to consider how individual parameters may vary across a catchment, and even at the field scale. This will be of particular importance for future upscaling and modelling methods, which currently often rely on a very small quantity of values to represent whole-catchment processes or parameters.

7.5. Areas for further research

Through its contributions to the currently growing NFM evidence base, this thesis has also highlighted a number of recommendations for future research. It should be stressed that whilst this thesis has responded to the call for empirical NFM evidence by producing and analysing datasets for a specific number of measures in SW-England headwater catchments, there is still a considerable step to be taken within the academic literature before our confidence and knowledge with NFM reaches that of traditional and hard engineering flood management. Based on the results and findings of this thesis however, a number of specific recommendations can be made, which aim to make specific proposals and are in addition to site-specific recommendations made within each respective research chapter.

7.5.1. Installation of temporary monitoring projects alongside NFM construction

Through the field monitoring conducted in this thesis, it was found that deploying field monitoring prior to NFM construction was infeasible due to the uncertainties of where measures were to be deployed and the short time frames between NFM project decision making and the start of construction. It is undeniable that gaining before-after-control-intervention (BACI) datasets offer numerous advantages for evaluating the impacts of NFM (eg. see Shuttleworth *et al.*, 2019; Black *et al.*, 2021; Puttock *et al.*, 2021), and thus has been recommended as a key factor within future NFM assessments (eg. Ellis *et al.*, 2021). However, the infeasibility of this in many circumstances should also be emphasised and therefore recommended here is that future NFM monitoring projects should focus on temporary installation alongside NFM construction to inform stakeholders and contractors how the structures could be best improved or altered following construction. For example, in chapter 3, key to pond efficacy at Halsewater was the inlet heights that filled the pond from the channel during high flows. It has been accepted in recent NFM literature that achieving this ideal filling threshold during design and NFM construction is challenging.

Thus, there are many potential benefits of a flexible NFM structure, where adaptations and adjustments (eg. to inlet heights) can be informed based on quantified data. The quantification of flow and system attenuation for NFM storage features can be used to examine whether the features are functioning as designed and as optimally as possible for attenuating floodwater. This may be particularly beneficial in new NFM catchments and where new or alternative structure designs are being deployed and the impact of the structure is not clear until the system is fully operational.

In addition, future temporary monitoring projects should aim to address key uncertainties in flow monitoring, identified in this thesis. Firstly, issues of rating curve uncertainty, resulting in a lack of confidence over the highest flow volume values at the studied leaky woody dam sites (see chapter 4), could be addressed through concentrated efforts to improve flow rating measurements. This may be particularly beneficial to gain measurements at high flows, to reduce the reliance on rating curve extrapolation, which ultimately adds additional uncertainties to the flow volume values extracted from the analysis. For this to be possible, projects will require group work for stage-discharge data collection (rather than individual, as conducted in this thesis), or substantial additional funds to install fixed flow meters in-channel.

The expansion of temporary monitoring projects alongside installation could also benefit future soil management trials. In chapter 6, runoff plots were used to test for overland flow under both trial and control sections of the field. To expand on this methodology in future projects, testing could occur in both field sections both prior to and after any soil management practices, enabling a BACI approach. Future monitoring could also include the expansion of testing to cover a wider catchment scale, to assess the impact of larger-scale soil management improvements (for instance over a series of adjacent farms, rather than part-field trials) and the potential impact on river flows downstream. This would involve both hillslope overland flow monitoring (as conducted in chapter 6) and in-channel flow monitoring (as conducted in chapters 3-5), over a considerably larger scale than possible through the field-scale measurements conducted in this thesis. Landowner participation over a small catchment area would be required for this research, along with an adequate time window before any interventions and a comparable control catchment.

7.5.2. Quantification of the impact of online water storage ponds for NFM, based on inflow and outflow comparisons

This next recommendation is specific to the challenges encountered whilst monitoring at Wellhams (chapter 5, where the generation of flow data was not possible. This chapter highlighted the potential of online storage ponds to attenuate large volumes of water during rainfall events and particularly in response to outflow management. A next important step in assessing the impacts of online water storage pond would be to monitor flow upstream and downstream of ponds, to conceptualise system inflow and outflow and to enable the more comprehensive analysis of event dynamics (as conducted at Halsewater and Merriott storage ponds, see chapter 3). This would also present an interesting perspective and comparison if this monitoring could occur at another online storage pond site with local management. Limited evidence could be located of a site that presented the interesting characteristics of Wellhams, principally that it was a large online storage site that was installed as an NFM feature (rather than within a traditional or hard engineering flood management scheme) and was also extensively managed and regularly maintained by a community flood group (CFG).

7.5.3. Upscaling of NFM empirical datasets within a modelling framework to examine the impact of NFM at the catchment scale

It is important to highlight that whilst individually, the produced empirical datasets demonstrate how NFM features are operating at the local scale, the generation of datasets that conceptualise hydrological processes which operate widely across the catchment (eg. hillslope to the river channel) is vital for future NFM characterisation within modelling frameworks. For instance, it is widely accepted that extensive configurations of different NFM measures, distributed widely across a catchment, in conjunction with traditional flood management features, is likely to produce the most optimal scenario for future flood risk management (Kay *et al.*, 2019; Ellis *et al.*, 2021; Muhawenimana *et al.*, 2021). Therefore, the production of empirical datasets that quantify the key hydrological processes that are operating across different catchments to generate system flow stores and releases, is vital to enable future characterisation of NFM features are that deployed throughout the catchment.

Using the expanding network of empirical datasets that have monitored key hydrological parameters associated with NFM (eg. to include those produced in this thesis), developments in catchment-scale modelling can be validated, enabling a full integration, and coupling of field-based and modelling findings. Whilst marked developments in NFM modelling applications are occurring (eg. Metcalfe *et al.*, 2017; Dixon *et al.*, 2019; Nicholson *et al.*, 2019; Goudarzi *et al.*, 2021) the further expansion of this work highly depends on the simultaneous production of observational data. The characterisation of NFM within modelling frameworks will enable alternative arrangements or clusters of NFM strategies and their connectivity to be tested.

Through the expansion of information regarding different hydrological parameters and catchment characteristics produced through the generation of new empirical datasets, a range of NFM configurations may be replicable in a variety of catchment types within a modelling framework. This may also enable future comparisons of the storage potential of constructed, designated storage areas (eg. offline ponds) versus agricultural management methods (eg. subsoiling) conducted at the field-scale to improve the water holding capacity of soil. For example, whilst the Halsewater water storage ponds offer the potential to store a total of 2987m^3 across both ponds for flow by diverting it from the channel, future studies may examine the area of soil structural improvements required (eg. through subsoiling or other agricultural management methods) to produce an equivalent water storage area.

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