The effects of upstream Natural Flood Management on urban surface drainage performance

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The evaluation of rural Natural Flood Management (NFM) has traditionally focused on the ability of interventions to mitigate downstream fluvial flooding by attenuating catchment response. This research expands this focus – investigating whether these same interventions could also mitigate surface flood risk in downstream urban areas. By moderating water levels in receiving watercourses, upstream NFM could promote free discharge from urban drainage outfalls and thereby improve local surface drainage performance.

A novel modelling methodology has been developed to characterise the response of three separate catchments – the Bin Brook in Cambridgeshire, the Asker in Dorset and a sub-catchment of the upper Calder in Yorkshire. The upstream, rural response is simulated by coupling Dynamic TOPMODEL (a semi-distributed hydrological model) and HEC-RAS (which solves the shallow flow equations). This offers a freely-available, spatially-informed approach for the evaluation of a range of upstream NFM interventions (located both within and beyond the riparian zone) at a catchment-scale. This modelled rural response then provides the input for a downstream, integrated urban drainage model (Infoworks ICM). This is then be used to examine how any consequent changes in outfall inundation by the urban watercourse alter local drainage performance.

Each case study is examined separately before a comparative study of all three is undertaken to identify broader trends.

These trends suggest that during more frequent events (e.g. 1 in 10 year), upstream NFM interventions create the greatest reductions for the time low-lying outfalls are submerged by local watercourses. As storm severity increases (heightening risk of drainage surcharge or failure) these reductions diminish. Despite this, the slight delay in rural response continues to allow more water to escape surface systems before outfall inundation occurs, increasing the effective capacity of networks and reducing surface flood volumes.

While any improvements to outfall discharge would not, in themselves, justify NFM implementation, these interventions have the potential to contribute to a downstream water level management strategy in certain locations and therefore will be of interest to urban flood risk practitioners.

It's man against the elements!
Conscious being versus insentient nature!
My wits against your force!
We'll *see who triumphs!*

– Calvin and Hobbes comic strip by Bill Watterson, 3rd May 1992

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

In May 2019 the Environment Agency Chair, Emma Howard Boyd, launched the Environment Agency's new long-term strategy for tackling flooding and coastal erosion with the words: "We cannot win a war against water. We cannot expect to build our way out of future climate risks with infinitely high walls and barriers," (Environment Agency, 2019a). The average annual economic loss from flooding between 1990 and 2014 was £250 million (Thorne, 2014), but the new EA strategy was primarily a response to several significant flooding events in recent years. Multiple events during the winter of 2013-14 caused an estimated £1.3 billion of damage in England and Wales (Reynard et al., 2017). December 2015 was the wettest month ever recorded, with three events (Desmond, Eva and Frank) causing flooding which affected 36,000 people, nearly 21,000 properties with a total of £1.6bn of economic losses (Environment Agency, 2018). Since the release of the new strategy from the Environment Agency (EA), there have been further significant flooding events in November 2019 and February 2020. Last year's flooding affected at least 1750 properties across Yorkshire, Derbyshire, Nottinghamshire and Lincolnshire (Parveen, 2019). Earlier this year (2020) saw the wettest February on record in the UK, with over 3,300 properties being flooded across England alone (BBC News, 2020). The UK currently has 1 million homes that have a higher than 1% chance of being flooded each year (Barker, 2019). The Government plans to spend £5 billion on flood defences between 2020 and 2026 (Rhodes, 2020), but it has been suggested that just to maintain the current level of flood risk will cost £1 billion annually by 2035 (Bracken et al., 2016).

This thesis focuses primarily on surface flooding but also refers to fluvial flooding. Fluvial flooding occurs when normal river channel boundaries are insufficient to convey water volume (Chen et al., 2010). Surface flooding is an umbrella term, typically referring to flooding in urban areas during heavy rainfall through pluvial, fluvial, groundwater and sewer flooding mechanisms (Falconer et al., 2009). There is increasing recognition of the threat from surface flooding (Webber et al., 2019). Indeed, the EA's 2018 annual flood management report found 3.2 million properties at risk of surface flooding (324,000 of which were 'high risk') (Environment Agency, 2018). This compares with the 2.4 million properties susceptible to fluvial flooding, of which 239,000 were at high risk. Overall, surface flooding accounts for 54% of the total flood risk to domestic properties in England (Fielding, 2017).

Traditional or 'structural' management of flood risk relies on hard-engineered solutions (walls, pipes, large storage etc.) to transfer flood risk from one location to another (typically downstream) (Bracken et al., 2016). This centralises and clarifies responsibility, while offering confidence in performance to given risk standards (Johnson and Priest, 2008). However, since the mid 2000s there has been gradual evolution of national flood risk management strategies to allow greater emphasis on sustainable development and 'making space for water' (Benson and Lorenzoni, 2017; Johnson and Priest, 2008).

This evolution was crystallised by the seminal Pitt Review (Pitt, 2008), which was published in response to the UK 2007 floods (which caused estimated damages of over £4 billion). One of Pitt's 92 recommendations was a call for clearer approaches to managing flood risk at a catchment scale and a better balancing of hard and soft-engineered interventions. This resulted in the growth of Catchment Based Flood Management (CBFM) philosophies, which aim to bring traditional flood risk management into greater alignment with other environmental and water quality objectives at a catchment-scale (Collentine and Futter, 2016; Huq and Stubbings, 2015; Mainstone and Wheeldon, 2016). Support for these approaches for mitigating flood risk has grown with the recent flooding events (Weston, 2020), though some remain sceptical (Wynne-Jones, 2016).

Lane (2017) defines CBFM as the manipulation of stream discharge in certain locations (e.g. a downstream urban area) and at certain times (e.g. flood peak) using spatially discrete interventions. This manipulation can be achieved by upstream alterations to land management, river channels, floodplains or reservoirs (Dadson et al., 2017). To date, such strategies have been evaluated primarily on their ability to mitigate downstream fluvial flooding.

While pertinent, there has so far been little nuanced consideration or incorporation within the CBFM philosophy of the constituent urban hydrological response. Indeed, the design and evaluation of urban drainage is commonly assumed to be isolated from the surrounding catchment response. More particularly, any potential for the interaction of rural and urban responses to mitigate or exacerbate urban flooding has received little attention. Consequently, the argument for CBFM interventions to mitigate fluvial flooding omits the prospect of the same interventions also playing a role in managing surface flood risk in urban areas.

To date, Natural Flood Management (NFM) interventions have been the primary technique used in CBFM strategies (Lane, 2017). These are 'green' interventions in rural environments (examples include afforestation, moorland restoration or floodplain reconnection) aimed at 'slowing the flow' and attenuating rural catchment response (a detailed discussion is given in section 2.2). They mirror Sustainable Drainage Systems (SuDS), which are an established form of 'natural' source control technique in urban flood management whose multiple benefits have been widely reported (Alsubih et al., 2017; Hamel et al., 2013; Hoang and Fenner, 2015; Pappalardo et al., 2017). There has been an evolution of terms and philosophies in urban flood management in recent years (e.g. Water Sensitive Urban Design, Water Sensitive Cities, Integrated Urban Water Management etc.) Fletcher et al. (2015). This PhD examines how NFM interventions in rural environments could also contribute to such urban flood management strategies.

Ferguson and Fenner (2020d) used the term 'rural-urban interface' to represent the points of interaction between rural surface water and urban drainage. Figure 1.1 contextualises this interface by idealizing surface flow pathways through rural uplands down to (and including) an urban response. It identifies two forms of flow crossing from the rural area into the urban environment (and so may have impact on the functioning of an urban drainage system).

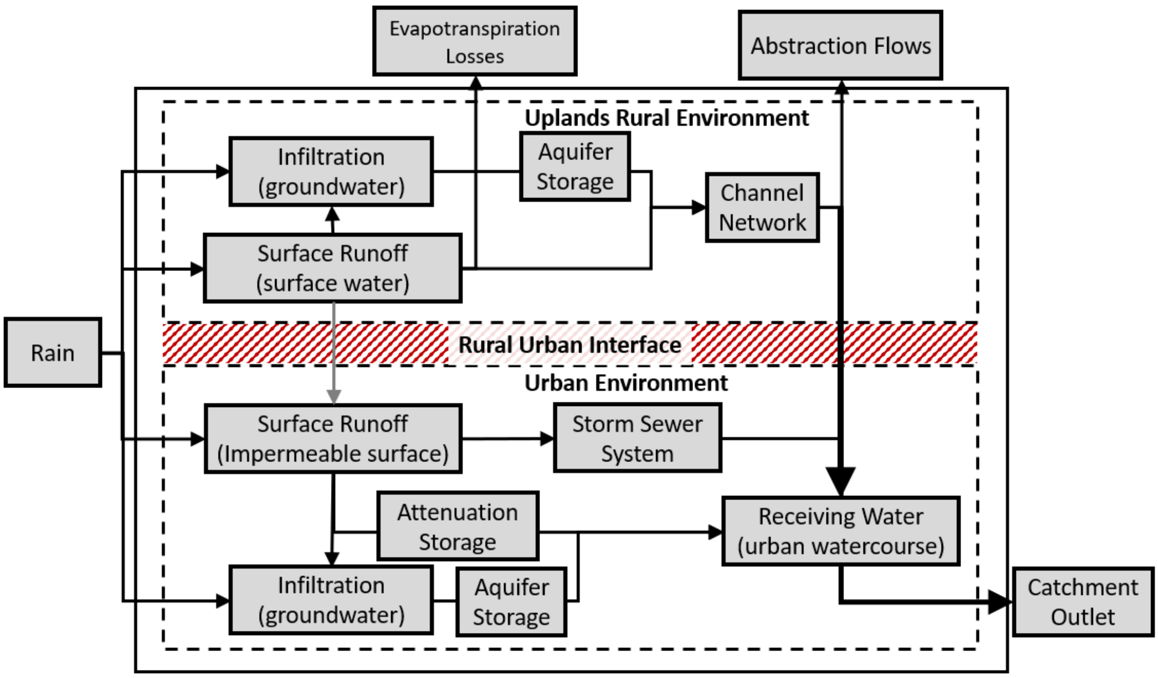

Figure 1.1 Catchment flows and the rural urban interface (from Ferguson and Fenner (2020d))

The first is rural surface runoff not captured by land drainage systems which can drain into adjacent urban areas and contribute to urban surface water. This issue has been recognised to a limited extent (Vaes et al., 2009; Yu and Coulthard, 2015).

However, this PhD focuses on the second (and bolder) flow path in Figure 1.1. The channel network drains the rural uplands before passing through the urban environment, becoming a receiving watercourse for the nearby surface drainage network. In responding to an event upstream, this receiving watercourse has the potential to inundate drainage outfalls and prevent discharge from the urban system. Potentially, this could reduce the effective capacity of the drainage network, create surcharged flow conditions and may eventually lead to surface flooding within urban areas.

By moderating flows (and water levels) in the receiving watercourse, upstream NFM across rural areas might have the capacity to promote free discharge from drainage outfalls, thereby improving performance of the urban system. Prevention of discharge from outfalls has been recognised as an exacerbating factor in surface flood risk (Ellis and Viavattene, 2014) (this problem is fully contextualised in section 2.3.1). In mitigating such a risk, an argument could be made that CBFM offers the potential for synergistic flood risk mitigation across rural and urban environments (rather than having a purely fluvial focus).

1.2 Research Question

The central research question of this thesis is:

What effect can catchment-scale Natural Flood Management interventions have on the performance of downstream urban surface drainage systems?

Beneath this central question sit three sub-questions which will each require careful evaluation. These are:

1. **What attenuating impact does upstream NFM have on the catchment-scale response in the urban watercourse?**

   The evidence behind catchment-scale impact from NFM remains nascent and cannot be assumed or inferred (Iacob et al., 2017; Lane and Milledge, 2013). Full consideration of the ability of NFM interventions to influence flows and levels in urban watercourses will be required.

2. **To what extent does inundation of outfalls by the receiving watercourse influence surface drainage response?**

   Surface drainage outfalls are commonly assumed to be free-draining (for instance the modelling for the updated UK National Flood Map for Surface Water assumed this (Environment Agency, 2019c)). As a result, there has been little examination of the likelihood and consequences of outfall inundation. To establish any potential benefit from upstream NFM interventions, the detrimental impact from this phenomenon must first be understood.

3. **How is drainage performance affected by moderation of levels in the receiving watercourse?**

   The upstream attenuation of catchment response created by NFM will influence the time outfalls are inundated. The resultant changes in drainage performance will need to be quantified and contextualised to establish the degree of benefit achieved.

1.3 Thesis Structure

The response to the central research question described in section 1.2 will be built across ten chapters.

Chapter 1 provides background to the concept of CBFM, contextualises the 'rural-urban interface' and introduces the central research question.

Chapter 2 evaluates the current evidence-base for NFM in the UK as well as discussing the role of Catchment Management Partnerships. This discussion is used to justify the chosen modelling methodology presented in Chapter 3. It also briefly introduces concepts behind surface drainage before reviewing instances of outfall inundation exacerbating flood risk.

Chapter 3 details the constituent parts of the novel modelling methodology and the nature of their coupling. There is also discussion and justification on the representation of NFM interventions. Sources of uncertainty are identified and discussed.

Chapter 4 gives a brief overarching introduction to the three case studies

Chapter 5 applies the modelling methodology to the Bin Brook catchment (the first case study catchment) to evaluate the performance of an urban drainage system for a west Cambridge housing estate.

Chapter 6 applies the modelling methodology to the second case study catchment. It evaluates the impact from the Asker River on a small urban surface drainage system in the town of Bridport, Dorset.

Chapter 7 applies the modelling methodology to the third and leading case study catchment. It evaluates the impact from the Calder river on a series of discrete surface drainage systems in the downstream town of Todmorden, West Yorkshire.

Chapter 8 extends the work completed in Chapter 7 by investigating the central research question through a focus on (i) climate change and (ii) variable storm tracks.

Chapter 9 analyses the results from all three case studies to identify possible broader trends and suggest how these findings might be of use in practice. The influence of uncertainties in the underlying methodology is critiqued before recommendations are made for further work.

Chapter 10 directly responds to the central research question and its sub-questions as set out in section 1.2.

Chapter 2

Background

2.1 Introduction

The reviewed literature for this thesis is spread across two chapters.

The purpose of Chapter 2 is to provide further context from the relevant research literature for the central research question. It does this by evaluating the current state of NFM in the UK (section 2.2) and also by reviewing the management of surface flood risk in the UK (section 2.3) before presenting the problem of outfall inundation and considering examples where the phenomenon has been known to exacerbate flood risk (section 2.3.1).

Section 2.4 concludes by summarising the value and novelty of evaluating catchment-scale NFM within a water level management strategy to influence performance of urban surface drainage.

The first part of Chapter 3 continues to review relevant literature on previous studies in order to support the justification of the selected research methodology.

2.2 Natural Flood Management

Natural Flood Management interventions aim to 'slow the flow' in rural catchment uplands in order to mitigate fluvial flooding for particular downstream reaches (Dadson et al., 2017). They do this by altering, restoring and using landscape features (Parliamentary Office of Science and Technology, 2011). There are many different forms of intervention, which can be broadly categorised into three types (Pitt, 2008):

- Promoting water retention through management of infiltration and overland flow. Examples of this type include: cross slope woodland (Figure 2.1(d)), headwater drainage management (e.g. moorland grip blocking) or farmland management (e.g. ploughing regimes).

- Retaining water by managing connectivity and conveyance.
  Examples of this include: runoff attenuation features (Figure 2.1 (b)), in-channel woody debris (or 'leaky barriers'), riparian vegetation (Figure 2.1 (a)) or preventing preferential pathways (e.g. 2.1 (f)) through appropriate farmland management.

- Making space for water by managing floodplain conveyance and storage.
  Examples here include: river remeandering (Figure 2.1 (e)), wetland restoration, floodplain reconnection or large bunded storage (Figure 2.1 (c)).

The literature broadly agrees that the evidence base behind NFM interventions having a significant impact on downstream flows, particularly at a catchment-scale, remains nascent (Iacob et al., 2017; Lane and Milledge, 2013; Waylen et al., 2017). Several contributory factors have been suggested to explain why firm conclusions about the effectiveness of NFM (on catchment-scale flows) have been slow to evolve. These are discussed below.

2.2.1 Form of Intervention

There is a wide range of different interventions, as summarised above (and exemplified in Figure 2.1), with each form impacting the hydrological system in different ways. This variation inhibits the capacity for any simple synthesis of the evidence for the overall impact of NFM.

Nevertheless, there have been several attempts at least to collate the results from individual NFM interventions. Their purpose is often to promote further physical implementation, doing this through a balance between: (1) demonstrating practice and funding sources through 'user-friendly' summaries of interventions and (2) presenting systematic reviews of evidence from (primarily academic) studies. An example of one focusing more on the former is Cumbria Strategic Flood Partnership (2017), a report offering summarising interventions tailored for farmers and their land practices, with information given on funding sources and maintenance costs. Similarly, (East Devon Catchment Partnership, 2020) provides an overview of different interventions focused on improving capacity of underlying soil (tailored specifically for stakeholder use in the South West).

Conversely, other reports amalgamate many different academic studies in an effort to better qualify the confidence that might be assigned to the impact of a given intervention. For instance, Quinn et al. (2013) (produced through Newcastle University) uses the results from three test watershed studies to indicate Runoff Attenuation Features (RAFs) can have

(a)

(b)

(c)

(d)

(e)

(f)

Figure 2.1 (a) Riparian vegetation in Stroud Catchment; (b) Runoff Attenuation Feature in Belford Catchment; (c) Bunded storage in Pickering Catchment; (d) cross slope tree planting in the upper Calderdale; (e) river remeandering in Swindale Catchment and (f) preferential pathway underneath a gate in the upper Calderdale

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(a) from Will Frazer (NFU)
(b) from NERC Website
(c) from UK Government Website
(e) from Lee Schofield (RSPB)

influence on small catchment response (but also highlights dependencies such as location and storm sequencing). Likewise, Stratford et al. (2017) reviews tree planting studies around the UK (and in comparable climates), finding a majority (36 out of 45) tree cover projects reduced fluvial flood peaks, although a further 12 reported no influence. O'Connell et al. (2004) reviewed evidence of land management practices, finding substantial supporting evidence of runoff mitigation at field scale, but very limited support for catchment scale impacts (discussed further in section 2.2.2).

There have been three key documents in recent years that have attempted to summarise and analyse the overall evidence about NFM implementation to date. These are:

1. 'The Natural Flood Management Handbook' (Forbes et al., 2015);
2. 'A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK' (Dadson et al., 2017);
3. Working with Natural Processes to Reduce Flood Risk (Burgess, 2017).

The first document leans towards a digestible overview of a range of NFM interventions to aid project delivery. It was produced by the Scottish Environment Protection Agency (SEPA), who have a significant knowledge base – Scotland was one of the early adopters of the NFM philosophy. Werritty (2006) and Cook et al. (2016) argue that the country has become a focal contributor to the evidence behind interventions. The handbook also uses case study examples but does not interrogate confidence in intervention impact.

The second is a Royal Society journal paper, authored by many of the leading experts in this subject area. This struck a highly cautious tone, concluding "the evidence does not suggest [..] interventions will have a major effect on most extreme events." Amongst several recommendations, it highlighted the need for monitoring to determine efficacy of interventions (although it also offered an hypothesis of the relative impact of different forms – see figure 2.2(a))

Finally, there is the EA's Working with Natural Processes (WwNP) evidence base, with aims to span both approaches referred to earlier in relation to collated summaries. It uses evidence from 65 case-studies around the UK and has produced fourteen 'one-page' synopses of NFM interventions. These summaries each have confidence intervals accounting for both the amount of evidence and the level of agreement within the evidence. Released alongside this was the 'NFM National-coverage Opportunity Mapping'.

There has also been some interesting discussion in the literature over what interventions can be appropriately identified as 'natural'. It has been argued that by allowing 'altering landscape features' (as defined above in section 2.2), NFM interventions could have dubious

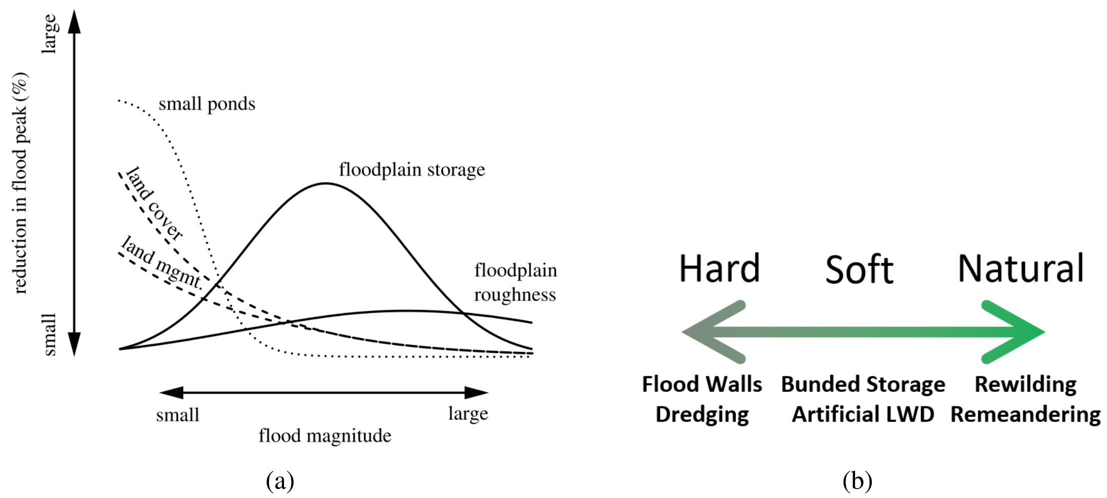


Figure 2.2 (a) Hypothesised intervention impact (from Dadson et al. (2017)) and (b) the spectrum of ‘naturalness’ behind catchment-scale interventions for mitigating flood risk (from Environment Agency (2012))

‘natural’ credentials with minimal benefits for surrounding biodiversity (Johnstonova, 2009). An example of this *could* be the bunded storage pictured in Figure 2.1 (c). A report from the Environment Agency (2012) comments further on this, pointing out that there is a continuum of interventions that work with natural processes to (potentially) mitigate downstream interventions. This continuum is summarised in Figure 2.2 (b). At one end are engineered interventions that heavily modify their environment. At the other are those that have a restorative effect on hydrological systems. Indeed, Carver (2016) argues that ‘rewilding’ should be seen as the epitome of natural flood risk management.

2.2.2 Influence of Scale

There is agreement in the literature that evidence for impact weakens as the scale at which interventions are evaluated increases (Dadson et al., 2017; Parrott et al., 2009). There have been many studies (of varying intervention) that have confirmed an NFM-influenced response at a field scale (Hygelund and Manga, 2003; Marshall et al., 2009; Nicholson et al., 2012). However, it should also be noted that there are those that have not – for instance, Pilkington et al. (2015) found little evidence that moorland restoration and gully blocking in the Peak District had any effect on percentage runoff.

This issue of upscaling has been attributed to several factors. Hill slopes can be thought of as low pass filters, transforming variable rainfall into inputs for downstream channel flow (ignoring losses through groundwater). Dispersion (hydrodynamic, geomorphological and kinematic) means this transformation involves significant attenuation (Di Lazzaro et al., 2016). A hill slope NFM intervention aims to further attenuate this response. The uniqueness of hydrological systems (discussed in Beven (2000)) means the intervention's impact on downstream flow conditions is dependent on location (Pattison and Lane, 2011). In other words, two identical interventions (even if located across the same hillside), would have different impacts on downstream response.

This effect is compounded by the subsequent phasing of sub-catchment responses at river channel confluences, something Pattison et al. (2014) highlights as critical in determining catchment scale response. It has been hypothesised by several authors that NFM (including interventions within the riparian zone) could play a role in the degree of synchronisation between tributaries (Dixon et al., 2016; Hankin et al., 2017; Leakey et al., 2020). There is a paucity of evidence on interventions' ability to do this (especially given dependence on factors such as antecedent condition or storm track) and Burgess-Gamble et al. (2017) highlighted this as a key research gap.

In discussing the role of scale in NFM evaluation, Lane (2017) states that intervention impact diminishes the further it is evaluated downstream. Ewen et al. (2013) highlights the need for properly identifying causal links between intervention impact at a local scale (e.g. $< 1ha.$) to large catchment scale (e.g. $100km^2$). There have been physical studies in small catchments that, with sufficient land use change and gauging data (a problem discussed in section 2.2.4), have drawn tentative causal links. For instance, Archer (2007) evaluated two adjacent catchments in Plynlimon ($10.5km^2$ of rough pasture and $8.7km^2$ of largely forested area), and found tangible differences in long term flow conditions downstream. Similarly, offline runoff attenuation ponds have been shown to reduce (modest) flow in the Belford catchment ($5.7km^2$) (Nicholson et al., 2020).

These studies have contributed to the observational evidence behind the generally accepted idea that interventions have been shown to reduce peak flows in small catchments of up to $\sim 10km^2$ (Hankin et al., 2017; Lane, 2017; Wilkinson et al., 2014a).

2.2.3 Multiple Benefits

NFM interventions offer opportunity for multiple benefits beyond any fluvial flood risk mitigation. These 'multiple benefits' – although dependent on intervention type – can include potential improvements for: (i) habitat creation through diversification of hydraulic channel behaviour (Gilvear et al., 2013) (ii) improved water quality through removal of sediment or pollutants using riparian roughening (Janes et al., 2017b; Yang et al., 2015), (ii) aquatic biodiversity (Rossi et al., 2010; Thompson et al., 2018), (iii) reducing soil nutrient losses

(Wilkinson et al., 2014a) and (iv) wider societal benefits (Teal and Peterson, 2005). McLean et al. (2013) argues there is insufficient emphasis and quantification of these multiple benefits.

However, multiple benefits of NFM have increasingly been evaluated from two distinct angles. The first is their ability to add additional 'economic value' to an intervention. For instance, Dittrich et al. (2019) carried out a detailed cost benefit analysis of a tree planting NFM intervention in a rural Scottish catchment, finding that positive net present values (NPV) only ensured when considering the wider ecosystem benefits of the intervention. Similarly, DEFRA (2015) produced cost benefit ratios for interventions in the Pickering catchment, finding ratios of 1.3 and 5.6 for the large bunded storage (picture in Figure 2.1(c)) and woodland features respectively. It is worth noting that in recent times, DEFRA have required a cost-benefit of at least 8 to approve a scheme (Mason, 2014). Again, these ratios were heavily influenced by the additional benefits accrued, primarily in the form of 'climate regulation' (i.e. carbon capturing by planting woodland).

While not yet frequent, such detailed economic analyses strengthen the argument behind NFM implementation (Wingfield et al., 2019). This is exemplified by CIRIA's recent update of the B£ST tool to include natural capital accounting of NFM interventions (Shaffer and Simmons, 2018). Although monetising natural benefits is still disputed, it offers a metric to directly compare with engineered structures (something Dadson et al. (2017) highlight as a key research need). However, Dixon et al. (2018) point out that for some interventions, benefits may not be fully realised before maturity (e.g. tree planting).

The second angle with which multiple benefits are evaluated is their ability to aid physical implementation through widening of stakeholder engagement. Stakeholder engagement has become recognised as critical in NFM implementation (Howgate and Kenyon, 2009). Posthumus et al. (2008) state, during a stakeholder workshop for NFM implementation in two small catchments in North Yorkshire, that participants highlighted the importance of ancillary benefits – pollution control, wildlife and landscapes. Old et al. (2018) report on a catchment scale project in the Evenlode, highlighting how a 'multi-objective' approach can be delivered with significant local stakeholder involvement (agreeing with findings in Rouillard et al. (2014)). Rouillard and Spray (2017) highlight how consideration of multiple benefits can help meet the different priorities within local implementation groups (discussed in section 2.2.4.1. Holstead et al. (2017) reported "NFM implementation may benefit from better integration of public policies [...] (e.g. WFD and biodiversity and urban planning policies)."

Indeed, there is an argument that the term 'Natural Flood Management' itself stymies intervention implementation because it focuses on uncertain flood mitigation credentials. Other synonymous terms, such as 'Working with Natural Processes' (WwNP) (Burgess, 2017;

Cooper and McKenna, 2008; Lavers and Charlesworth, 2017a) or ‘Nature Based Solutions’ (NBS) (Pontee et al., 2016; Short et al., 2019) are seen in the literature. These terms offer an immediately more holistic encapsulation of environmental benefits achieved when using natural processes to manage flood risk (Lane, 2017). However, their interchangeability has reduced clarity in their usage (Wingfield et al., 2019). This thesis retains the term NFM but continues to recognise the wider functions of such interventions.

2.2.4 Design, Implementation and Monitoring

Early implementation of physical NFM studies were typically conducted through academic consortiums or government projects in isolated, predominantly rural catchments with minimal stakeholder involvement. The primary purpose of these studies was to build an evidence base for various NFM types and benefits. Projects typically had sufficient resources for initial modelling studies and subsequent monitoring. Examples of such studies include the catchments of Pontbren (Wheater et al., 2008), Hodder (Ewen et al., 2013; Geris, 2012), Belford (Nicholson et al., 2012), Pickering (Odoni and Lane, 2010) and Parrett (Potschin et al., 2008).

However, following the Pitt Review (Pitt, 2008) and facing a growing need to address the water quality objectives required by the EU Water Framework Directive (primarily to achieve ‘good ecological status’ in all watercourses by 2027), the Department for Environment, Food and Rural Affairs (DEFRA) instigated the Catchment Based Approaches[1](CaBA) philosophy in 2011 (DEFRA, 2011). Designed to promote collaboration between local stakeholders to integrate water management at a catchment scale, the CaBA philosophy has provided an operational framework for stakeholder groups looking to manage their local water environment (Short, 2015). These groups have a variety of names, including ‘Catchment Partnerships’ (Old et al., 2018), ‘Catchment Management Groups’ (Cook et al., 2012) and ‘Catchment Management Partnerships’ (Rollason et al., 2018). This thesis uses the latter term to refer to all such groups.

Catchment Management Partnerships (CMPs) have become the typical vehicle by which national agencies (the Environment Agency, Natural England,the Rivers Trust etc.) interact with local public, private and community organisations (e.g. Lead Local Flood Authorities (LLFAs), water companies and environmental groups) to implement NFM projects (Old et al., 2018; Short et al., 2019). There were initially 25 ‘proof of concept’ case catchments (Short, 2015), but CMPs now implement the CaBA philosophy in over 100 catchments around the UK, with over 1500 participating organisations (Rouillard and Spray, 2017). The financial

[1] https://catchmentbasedapproach.org/about/

support behind CMPs can vary but, despite some central funding (e.g. the £15 million allocated to catchment-scale NFM measures by the UK government in Autumn 2016), their funding model relies on tightly budgeted projects. The primary deliverables for many of these are tangible, physical interventions.

The evolution towards CMPs implementing NFM has had repercussions for both (i) the role of modelling in any catchment-scale design and (ii) the emphasis of subsequent monitoring of intervention impact.

Catchment modelling design exercises, which must have sufficient resolution to incorporate the impact of NFM interventions, come under significant scrutiny because they (i) offer a potential economy within limited project resources and (ii) prolong project lead times (Wingfield et al., 2019). This problem is further magnified by (iii) the often large data requirements needed to construct models (iv) the uncertainty of representing NFM within a hydrological model (discussed further in section 3.8) and (v) the fact that the combinations required to understand optimal sets of interventions across a catchment can be computationally prohibitive (Lane, 2017).

Instead, catchment design has become more focused on opportunistic (or 'no regrets') approaches (Pittock, 2009). This assumes that any carefully contrived intervention will have sufficient benefit (e.g. slow the flow, if only very marginally, and other multiple benefits) to outweigh any negative consequence (Forbes et al., 2015; Pontee et al., 2016; Wilkinson et al., 2014b). There is some support for this philosophy in the literature – Iacob et al. (2014) reviewed the impacts of 25 different catchment scale NFM studies, concluding their implementation "evidenced overwhelmingly net positive benefits." In addition, both Howgate and Kenyon (2009) and Lavers and Charlesworth (2017b) recognise that the distributed nature of catchment-scale NFM makes implementation reliant on landowner engagement. Short et al. (2019) details a project in the Stroud catchment (which is discussed in depth later in this section) where the implementation strategy was based entirely on identifying sympathetic landowners.

Despite this increasing prevalence, there has also been some pushback against the opportunistic approach – Odoni and Lane (2010) demonstrated that NFM has the potential to synchronise tributary responses. Lane (2017) agrees with this, stating "if we slow the flow in all tributaries, we may end up with them all remaining synchronised." Another form of detrimental impact is highlighted by Bernsteinová et al. (2015), who found autumnal low flow conditions were exacerbated by afforestation in a small catchment in the Bohemian Forest (southern Germany).

A further repercussion of CMPs being largely responsible for NFM implementation is the shift away from appropriate monitoring. There are different techniques for monitoring

(a) (b)

Figure 2.3 (a) FRPB Flume (gauging $\sim 1km^2$ at a cost of $\sim$ £500) and (b) CEH mountain flume ($\sim 4km^2$ for $\sim$ £$50,000$) (These photos are courtesy of a NERC funded presentation by Barry Hankin and Nick Chappell)

intervention impact, ranging from event-based anecdotal reporting to continuous river gauging to capture influences on the flood hydrograph. The latter is generally considered the standard necessary to inform the evidence base (Holstead et al., 2016). Waylen et al. (2017) highlights that such monitoring using flow gauging structures can become more difficult and resource intensive at the farm-scale. Figure 2.3 gives an indication of how costs can increase dramatically as the contributing area being monitored increases. Pattison et al. (2014) argues that monitoring is further complicated by the fact that any catchment flow record will be influenced by uncertain climactic evolution, confusing any long-term 'before/after' gauging exercise (Pattison et al., 2014).

A recent survey by the EA found 52% of CMPs had no monitoring plan of any kind being implemented (Environment Agency et al., 2017). Moreover, Dadson et al. (2017) state "the lack of monitored baselines and experimental controls creates a risk that the wider and scale-dependent impacts cannot be properly investigated or used to inform decision making." Lavers and Charlesworth (2017b) agree, highlighting the need for both modelling and monitoring to be required if NFM is ever to provide a 'design standard' for flood protection. Interestingly, Bracken et al. (2016) surveyed practitioners who believed an idealistic view of NFM was creating a disconnect with the need for physical evidence that conforms to traditional expectations of flood risk management.

2.2.4.1 Catchment Management Partnerships

To contextualise these issues surrounding design, implementation and reliance on multiple benefits, the recent experiences of three CMPs are detailed here

- *Sussex Flow Initiative (SFI)*
  The SFI began in 2012 as a coordinated project between the Sussex Wildlife Trust, the Environment Agency and the Woodland Trust. The catalyst for the project was a hydraulic model of the River Uck, which suggested that Catchment Riparian Interventions Measure (CRIMs) could have a significant reduction on downstream flood risk. However, Fran Southgate (Wetlands Landscape Officer at the Sussex Wildlife Trust) stated that, on commencing the project, this modelling was found to be an inadequate basis for physical implementation because it had not considered landowner consents (F. Southgate, *pers. comm.*). An alternative hydrological modelling study was rejected as being too expensive for the project's annual budget of £50,000 (estimated modelling costs ranged from £40,000 to £200,000). This decision was reinforced by the dearth of available monitoring data – it was estimated that 10 years worth of gauging data would have been necessary to adequately quantify impact (F. Southgate, *pers. comm.*). She also stated that their rough approximation was that between 20 and 40% of catchment area would need to have woodland cover to have downstream impact on the hydrograph. Instead of detailed modelling, the SFI often satisfies funder requirements by doing high-level approximations of the storage created by interventions (e.g. they assume $1m^3$ behind each woody debris dam).

- *Stroud Rural Sustainable Drainage Project*
  The Stroud catchment scheme is perhaps the most well-known example of this landowner focused technique. The philosophy of the project is to rely on the sustained engagement of many local landowners to install woody debris dams (and other in-channel interventions) rather than a holistic plan for modelling, implementation and evaluation across the catchment. This approach has achieved a remarkably successful uptake rate with over 300 interventions across the large catchment area ($200km^2$) (Uttley and Skinner, 2017). There is no baseline data for the catchment and monitoring occurs primarily through observations (Short et al., 2019). However, isolated comparisons of flows (before and after installation of interventions) during heavy rain events have been used to produce some conclusions (Uttley, 2017). While reporting positive

impacts, this method is clearly limited. Therefore, reporting on the project relies on indirect impacts (similarly to the SFI). For example, it is reported that: “21% of the Stroud Frome catchment discharges through NFM features” (Uttley, 2017).

- *Medway Catchment Partnership*
  The Medway is an extremely large catchment (1388km^2) in Kent which is particularly susceptible to climate change – the Catchment Flood Management Plan predicts there will be a 40% increase in properties at risk from a 1 in 100 event by 2100 (Environment Agency, 2009). Still in its infancy, the Medway Catchment Partnership (led by the South East Rivers Trust (SERT)) aims to combat this by implementing a CaBA philosophy to a range of NFM interventions (Environment Agency, 2017). At an October 2017 introductory workshop, stakeholders produced two potential approaches which broadly follow the two already presented above (B. Davies, 2017 *pers. comm.*). Option (a) aimed to create publicly available maps for sharing catchment-scale opportunity and consulting on finding priority sub-catchments to target with interventions.Option (b) was five times the price (est. £24,000) but included detailed modelling (conducted by JBA) would allow quantification of NFM impact and understanding of synchronisation (Medway Catchment Partnership, 2017). The second annual action report from the Medway Catchment Partnership suggested that the option (a) has been preferred, with sub-catchments above Five Oak Green and Headcorn being targetted (Environment Agency, 2019b).

The experiences of these three CMPs reinforce the literature reviewed earlier in this section. The implementation of physical interventions is decided by the availability of landowner permission, with detailed modelling often being considered a dispensable expense. However, this is not a universal trend and there remain examples of local groups using detailed modelling. For instance, Old et al. (2018) reports on the CMP for the Evenlode catchment (Oxfordshire) using hydraulic modelling and ‘hydrological assessments of storage volumes’ to test different NFM scenarios (although installation was still primarily informed by national surface water mapping, catchment walkovers and landowner engagement). Impact is being evaluated through intensive monitoring (gauging has been installed for water level, quality and turbidity).

2.3 Surface Water Management

The purpose of surface water networks is to transfer storm water under gravity from a series of inlets within an urban watershed (often road gullies) to an outfall (Butler and Davies, 2011). These systems usually drain through underground pipes along a short thalweg to the nearest urban watercourse (or other sink). Failure of such systems (i.e. surface water flooding) threatens 3.2 million UK households (DEFRA, 2018). The design and review of urban hydrological systems now typically make use of integrated modelling to provide a known 'level of service' (Digman et al., 2014), partly because of the difficulty in establishing particular (often circumstantial) failure modes within surface drainage systems (Palla et al., 2018). Failure can be caused by multiple mechanisms (flow exceedance, blockage, poorly maintained systems etc.) that can interact to create instances of flooding unique to particular rainfall events (Kázmierczak and Cavan, 2011). This means the designed capacity of systems is often not known and varies significantly with different systems (Wheater, 2006). This unpredictability of failure goes some way to explain why two thirds of the 5 million people at risk from surface flooding in the UK are unaware that their property is in danger (Environment Agency, 2019a). This type of flooding also has significant repercussions for public services – for every one person who experiences flooding, 16 others are affected by disruption to other systems such as power transport and telecommunications (Environment Agency, 2019a). It has been estimated that it costs the economy £100,000 per hour for each major road impacted (Hooper et al., 2014; Pregnolato et al., 2017b).

The management of this surface water risk can also be traced back to 2008 Pitt Review. In fact, the review attributed two thirds of property flooding during the 2007 Somerset level floods to storm water overloading drainage systems (Priest et al., 2011). It also provided the catalyst for the creation of Lead Local Flood Authorities (LLFAs) and made the preparation of local flood risk management (LFRM) strategies a legislative requirement (Ellis and Lundy, 2016). Two key components of LFRMs are (1) CBFM plans (discussed above) and (2) surface water management plans (SWMPs) (Benson and Lorenzoni, 2017). SWMPs provide a strategy for identifying and managing local sources of surface water flooding (including sewers, drains, groundwater, surface runoff and small watercourses) (DEFRA, 2010). In many cases the impact of flows crossing the rural-urban interface (see Figure 1.1) will be minimal. However, the Surface Water Management Action Plan (DEFRA, 2018) highlights the creation of Drainage and Wastewater Management Plans (DWMPs) by water and wastewater companies in England and Wales for 2022 (DEFRA, 2018). The DWMP guiding framework (released by Atkins in September 2018) emphasises the importance of DWMPs linking with local catchment management plans (Atkins, 2018).

Urban surface drainage is typically built to function in intensities up to 5 year design rainfall events. However, with surcharge capacity, systems have latent storage (where the extra capacity is dependent on pipe depth) which makes the design flood event much less frequent – typically up to a 30 year storm (Butler and Davies, 2011). Surcharging of surface drainage is a well-recognised phenomenon in the literature (Fraga et al., 2017; Wheater and Evans, 2009). This thesis uses the definition given by the European Standard EN 752, which describes surcharging as: *"a condition where [..] surface water is held under pressure within a drain or sewer system, but does not escape to cause flooding."* Surcharging is distinct from consequent surface flooding, which occurs when *"surface water escapes from or cannot enter a drain or sewer system and either remains on the surface or enters buildings."* Surcharged conditions begin once the free water surface reaches the pipe soffit. This is shown diagrammatically in Figure 2.4. Extended periods of surcharging can eventually lead to surface flooding (Schmitt et al., 2004), although surface flooding resulting from drainage surcharge is often localised at manholes (Yu and Coulthard, 2015). In certain cases, this could be regarded as 'nuisance flooding'. Although typically used to describe coastal flooding (Haigh et al., 2017), the receptors from nuisance flooding are agreed to be public areas such as roads (or parks) where levels do not overtop curb height and do not become hazardous to property (Kirshen et al., 2015)

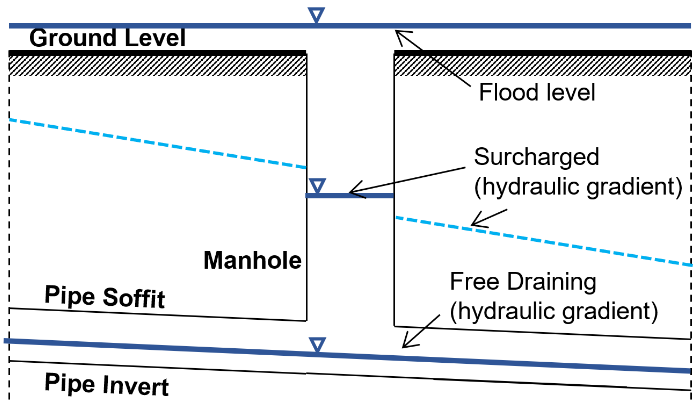


Figure 2.4 Classification of different manhole states (developed from Schmitt et al. (2004))

2.3.1 Inundation of Surface Drainage Outfalls

Surcharging and flooding of surface drainage can be caused (i) by the input through the gulleys exceeding capacity or (ii) some part of the system becomes blocked (Wheater and Evans, 2009). The latter is the focus here – namely when the receiving watercourse prevents free discharge through the surface drainage outfall.

Figure 2.5 defines four separate 'flow states' in an urban watercourse with an overhanging urban surface outfall. State 1 has a base flow in the urban watercourse. If there is no discharge from the urban outfall (state 1a), there is no interaction. In State 1b there is free drainage from the outfall into the watercourse, potentially causing a small backwater effect within the urban watercourse.

Depth (rather than flow) in the downstream urban watercourse is the primary variable considered here. In the subsequent modelling methodology (see Chapter 3), outfalls are assumed to be unable to discharge when the water level in the channel reaches the outfall invert (i.e. threshold of state 2 in Figure 2.5). This assumption is applied to a mixture of flapped and unflapped outfalls. It is a conservative assumption because there will be a period as the river level rises through the outfall pipe's height when some discharge from drainage will still occur.

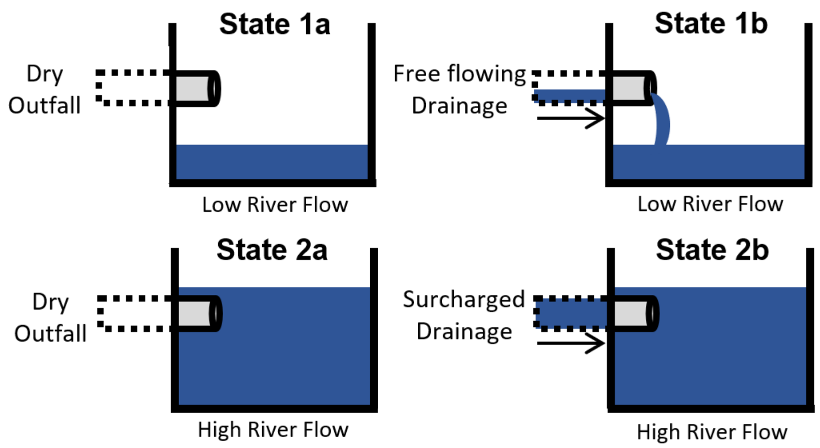


Figure 2.5 Different possible states of inundation in the downstream urban watercourse (from Ferguson and Fenner (2020d))

This is extremely complex behaviour, occurring quickly and therefore necessitating very short time steps in any model. To avoid the resultant increase in computational requirement, this assumption (that outfalls are unable to discharge when the water level in the channel reaches the outfall invert) was deemed pragmatic.

The water level at which the outfall invert is reached is termed the 'inundation threshold' and results in a 'drowned outfall'. If there is no flow within the urban system, no surcharging occurs (state 2a in Figure 2.5). However, in state 2b (when the urban response is ongoing), surcharging does occur, causing a reduction in capacity of the surface drainage network.

The inundation threshold is dependent on the local channel geometry and drainage outfall characteristics. With good design, so that significant head drop below the outfall exists even

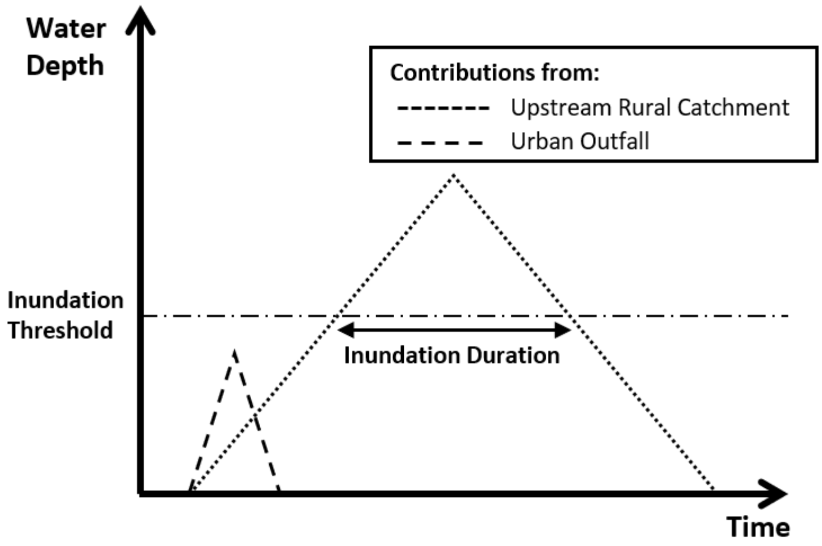


Figure 2.6 Hypothetical example of outfall inundation to define 'Inundation Threshold' and 'Inundation Duration' (from Ferguson and Fenner (2020d))

in high flow conditions, this threshold will not be reached (although this is dependent on topography).

Figure 2.6 presents a hypothetical interaction between the two contributing flows to the downstream urban watercourse. The urban sub-catchment, being much smaller and largely impermeable, is likely to produce a flashier response. The rural catchment, draining a larger and distant area, will typically contribute more flow and peak much later. In this case, the inundation threshold is exceeded, resulting in a 'inundation duration'. The result is an example of flow state 2a (see Figure 2.5) because the urban outfall has already passed through the system – no surcharging of the urban system would occur. However, a poorly designed outfall (or one constricted by local geography) could lower the inundation threshold. This would increase the inundation duration and thus the potential for surcharging in the drainage system.

To better understand the magnitude of this risk, it is appropriate to reflect on physical examples of inundated outfalls exacerbating flood risk. This problem has long been identified in coastal towns, where tide surges combined with heavy rainfall can mean blocked outfalls and insufficient subsurface drainage capacity to prevent surface flooding (Armstrong et al., 1989; Cartwright and Smith-Clapham, 1971). Ramsbottom et al. (2006) also highlighted within the Thames Estuary 2100 project the increase in flood risk from outfall flaps being closed more frequently by sea-level rise.

There are a limited number of examples of peer-reviewed study in the UK on the impact of river levels inundating surface drainage outfalls. Ellis and Viavattene (2014) reported a flood risk in Birmingham being exacerbated by outfall flaps being closed because of high water levels in the nearby River Rea. Similarly, Chen et al. (2010) identified the phenomenon during a modelled 50 year event in the Stockbridge area. Several Lead Local Flood Authorities (LLFAs) have also highlighted the problem. For instance, Jackson Hyder Consulting (2015) identified the restrictive impact of high water levels in local streams on the surface water network for the Kent town of Paddock Wood as a critical flooding mechanism. In Greater London, Kingston town centre and nearby Hogsmill Valley are areas susceptible to flooding as a result of high water levels in the local watercourse, thereby blocking outfalls and creating extended periods of surcharging in the surface drainage network (Craven and Littlewood, 2011).

Despite the issue not being the focus of extended study, there are numerous references to the *potential* of exacerbated surface flood risk resulting from inundated drainage outfalls (Bradbrook, 2006; Butler and Davies, 2011; Douglas et al., 2007; Houston et al., 2011; Santacruz et al., 2015; Zhu et al., 2016). However, drainage modelling exercises typically assume free discharge from an outfall as a downstream boundary condition. For example, the modelling behind UK's national 'Risk of Flooding from Surface Water' map, which is used by many LLFAs to inform their flood risk management, assumed free discharge from outfalls (Environment Agency, 2019c).

There are several reasons why the validity of this assumption warrants further examination. With increased uncertainty in future rainfall predictions for much of the UK (Committee on Climate Change, 2017), there is likely to be greater stress on the conveyance capacity of urban drainage systems (Arnbjerg-Nielsen et al., 2013; Dale et al., 2017). This is coupled with increased development in British towns and cities and an ageing surface water drainage infrastructure, much of which dates from the Victorian era (Thorne, 2014). Maintaining or improving an agreed 'level of service' will require greater evaluation of circumstantial factors inhibiting surface drainage performance (Palla et al., 2018). The 2019 progress report on preparing for climate change highlighted a lack in understanding in trends in vulnerability and exposure to surface water flooding (Committee on Climate Change, 2019). A 2011 study by Mott MacDonald for Ofwat found that sewer volumes will see a median increase of 51% during 10 year events by 2040 (as a result of both climate change and development) (Yorkshire Water, 2013).

While the full implications of climate change for inland drainage systems remain unclear, it is generally agreed that evolving precipitation patterns will result in significant changes to current levels and flows in receiving watercourses (Hannaford and Marsh, 2008; Stevens et al., 2016). Most climate projections agree the UK will have wetter winters and drier summers (Murphy et al., 2010), with extreme rainfall events more likely (Buonomo et al., 2007; Hannaford and Hall, 2012) leading to greater flow depths in urban watercourses during wet periods. This will make the need for a better understanding of drainage outfall behaviour even more acute.

A second concern in ensuring sufficient head drop below outfalls is the UK's continued urbanisation of low-lying floodplains. The proportion of impermeable surfacing in urban areas has increased by 22% since 2001 (Committee on Climate Change, 2019). The EA estimates the number of properties on floodplains will double across the next 50 years (Laville, 2019). While other mitigating measures are feasible (raised infrastructure, in-built system storage etc.), these are likely to be high in cost and do not necessarily offer the other benefits of upstream NFM.

2.4 NFM within a water level management strategy

Chapter 2 has evaluated two challenges, each in discrete paradigms of flood risk management. It is apparent that the inundation of surface drainage outfalls is often overlooked and that, in certain cases, this has exacerbated urban surface flood risk (section 2.3.1). At the same time, the still- nascent evidence base for the quantification of how NFM can mitigate fluvial flooding means that catchment-scale NFM projects now often look to other 'multiple benefits' to justify their implementation. Wingfield et al. (2019) argue that incorporating different multidisciplinary benefits into NFM strategies increases wider stakeholder involvement and creates greater opportunity for implementing interventions which may also mitigate fluvial flood mitigation. Thus, as they continue to search both for more stakeholder engagement and more project funding, CMPs are increasingly searching for new and where possible, quantifiable, multiple benefits for their local projects to help solve particular local problems.

The central research question (which is presented in section 1.2) evaluates the possibility of synergies between these two challenges.

It is postulated that by moderating water levels in urban watercourses, upstream NFM could be used to promote free discharge from surface drainage outfalls and thereby improve drainage performance. This provides an additional focus for how NFM might now be evaluated at a catchment-scale. Rather than evaluating any intervention's ability to manage downstream flow conditions (i.e. to prevent out of bank flow during extreme events), a key novel feature of this research is to focus on that intervention's role within a 'water level management strategy'.

To date, water level management strategies have primarily been the prerogative of Internal Drainage Boards (IDBs). IDBs are public authorities (funded by other local authorities, land occupiers and the EA) and there are over 110 IDBs in the UK (covering nearly 10% of

England's area) that invested a total of £61.3 million in water level management strategies in the 2016 financial year (Association of Drainage Authorities, 2017). Primarily in lowland areas (e.g. the Fens, eastern Yorkshire), these strategies provide asset security (e.g. flood risk mitigation, land drainage, transportation, water supply etc.) to the transport, agricultural, energy and environmental sectors.

However, in a catchment modelling study in North Yorkshire, Metcalfe et al. (2017) found that IDB regulations and management regimes constricted ability to implement in-channel woody debris. They conclude that "priorities [of IDBs] in terms of channel and runoff management are likely to diverge from those of NFM practitioners." Johnson and Priest (2008) went further and argued the responsibilities of IDBs have been curtailed by the emergence of catchment based flood management. This is because they represent a fragmented institutional approach to flood risk management (Benson and Lorenzoni, 2017). This is perhaps slightly unfair, given the many examples of IDB's contributing to restoration of natural systems (e.g. river restoration or floodplain reconnection) (Mainstone and Wheeldon, 2016).

However, by investigating the role of catchment-scale interventions on downstream water level, this research has clear relevance for IDBs looking to benefit from the emergence of NFM and take a more holistic approach to water level management (discussed in section 2.2).

From the perspective of an NFM practitioner, the shift in focus from flow management in rural catchments to water level management in urban areas would (if viable) represent benefit accrued from the same interventions across a range of more frequent events (i.e. with in-channel flow conditions). Evidence suggests that NFM can have greater attenuating impact in such interventions (Dadson et al., 2017).

It is also important to stress that NFM projects are developed, implemented and often managed by local CMPs. Each CMP will have not only its own unique set of physical catchment characteristics – it will also have its own set of stakeholder agendas and external pressures. In some cases, this has led to increased scrutiny over the benefits of modelling within the design of catchment-scale NFM. This evolution will partly inform the justification of the methodology given in Chapter 3.

Chapter 3

Methodology

3.1 Introduction

Chapter 2 contextualised the significance and value of the central research question. This chapter begins by reviewing further relevant literature to help evaluate the range of potential methodologies available for interrogating this question.

Having justified a chosen methodology, further details are provided about the application of the three component modelling tools – Dynamic TOPMODEL (section 3.5), HEC-RAS (section 3.6) and Infoworks ICM (section 3.9.1).

Chapter 3 continues by considering some of the implications of replicating the impact of NFM through numerical representation. It concludes with an explanation of the calibration procedures followed in the subsequent case studies plus a discussion of all relevant uncertainties.

This is the foundation for the case studies detailed in Chapters 4, 5, 6, and 7.

3.2 Available Methodologies

Initially, three separate general approaches to answering the research question were identified. These were:

1. Using data from a physical catchment study with an upstream NFM implementation project and a known outfall inundation issue in a downstream urban area as a way to measure the impact of that NFM project on the urban drainage system.

2. Combining available datasets from different watersheds to create a 'hybridised' catchment with which to evaluate the central problem.

3. A modelling approach using case studies to investigate the likelihood of outfall inundation and impact from numerical replications of upstream NFM interventions.

All three options had their strengths and weaknesses. Ultimately, the first option was discounted because (i) there are limited available studies with appropriate characteristics and sufficient data that would be required to address the central question (ii) any additional targetted gauging/measuring would be dependent on rainfall events during the study period and (iii) the uniqueness of single catchment would limit the scope of any conclusions. Likewise, it was felt that for the second option (i) any conclusions would not be related to a physical location and (ii) the uncommon methodological structure which might limit confidence in any conclusions. The final modelling methodology has its weaknesses (discussed in section 3.12) but does offer an ability to (i) evaluate the impact of outfall inundation initially across several different case study catchments (so that, if successful, wider application would be possible) and (ii) examine a variety of further hypothetical scenarios (such as climate change or storm direction) around the central question. A modelling methodology was therefore deemed the most appropriate approach.

3.3 Evaluation of existing modelling methodologies

There are a myriad of existing models and codes for approximating catchment hydrology. There is therefore limited value in this research developing new source code, particularly given the complexity in creating computational hydrology to evaluate the necessary systems across rural and urban environments within a catchment.

Section 1.1 contextualised the central research question by defining the 'rural-urban interface'. The immediate implication is a requirement that any modelling strategy must be able to explicitly represent multiple connected hydrological systems across a catchment within a single modelling framework. Therefore a 'holistic' modelling approach is required.

Numerical characterisation of these domains can be achieved through either (1) coupling various solvers together or (2) using a single integrated model. In order to identify and justify the preferred methodological procedure, a range of different previously used modelling approaches will now be evaluated with respect to their suitability for answering the central research question (section 1.2), while also recognising the recent scrutiny of modelling catchment-scale NFM (section 2.4).

Four criteria have been identified (through the context given in Chapter 2) to evaluate the ability of existing methodologies on their ability to :

1. characterise rural hydrological response at a catchment-scale;
2. replicate a range of NFM interventions in the rural environment;
3. integrate pipe flow and open channel flow within the urban environment;
4. be widely accessible and not require significant computational requirement.

Each criterion will now be discussed separately as part of a methodological review used to justify the final decision (given in section 3.4).

3.3.1 Catchment-scale rural modelling

Characterising the rural response can be achieved using hydrological, hydraulic or a coupled modelling approach – each will be discussed in this section.

3.3.1.1 Hydrological Models

Beven (2019) argues that the complexity of catchments' hydrological systems is such that the calibration of any model relies on integration of small-scale heterogeneities. Numerically representing these heterogeneities is dependent on model complexity. Beck (1991) first proposed classifying models in terms of increasing model complexity – 'metric' (also known as empirical), 'conceptual' or 'physics-based'. This classification has become a widely accepted in the significant literature evaluating catchment-scale hydrological modelling (Gayathri et al., 2015).

Empirical models (often regarded as 'black box' approaches) relate an input (e.g. rainfall) to an output (e.g. catchment-scale flow response) with no consideration of internal features or processes of the hydrological system. Being data driven, their oversimplified representation of constituent processes means they have poor predictive power (Euser et al., 2012; Gharari et al., 2015). Examples of long established empirical models used to convert rainfall to runoff include the rational method (Kuichling, 1889), Horton's model (Horton, 1933) and the revitalised rainfall-runoff method constructed by in the Flood Estimation Handbook (Kjeldsen, 2007). There are examples in the literature of empirical models being developed to characterise catchment scale response – for instance Langridge et al. (2020) present a new empirical structure (tested across over 150 river gauges around the UK) which compares favourably with the established FEH method. Another example comes from Wałęga et al. (2020), which develops a new catchment-scale empirical method for evaluating flows across a range of catchment sizes in the Polish Carpathians.

At the other end of the spectrum there are physically based models, which use continuum mechanics to represent hydrological processes (infiltration, evapotranspiration etc.) (Pechlivanidis et al., 2011). These typically offer higher confidence in any result and an ability to manipulate a wide range of physically measurable parameters (Bergström, 1991). They do have limitations however – Refsgaard and Storm (1996) suggest that the number of parameters subject to variation during calibration of a distributed hydrological model should be kept to a minimum. This is partly because of "the great spatial complexity of catchment systems and the great difficulty of obtaining sufficiently detailed spatial information," (Beven et al., 2015). Extrapolation of these processes is inevitable when modelling at catchment scale (thereby assuming constituent processes and properties considered by the model are independent of scale to some degree). Physically models are usually described as 'fully distributed', with the spatial distribution of process representation dependent on the grid square resolution. Sandu and Viirsta (2015) note that modelling of catchment response using fully distributed hydrological models is significantly influenced by grid resolution (as is the associated computational requirement). Two of the most well known physically based models are MIKE SHE and SHETran (both based on the same underlying Système Hydrologique Europeén structure) There are many examples of their application: Vázquez et al. (2002) uses MIKE SHE to characterise response from a $586km^2$ (with a $600m$ grid resolution) catchment in Belgium; Janes et al. (2017a) applies a SHETRan model to the $2400km^2$ Eden Catchment (northwest England) using a grid resolution of $1km$ and Refsgaard (1997) applies Mike SHE to a $440km^2$ (with a $500m$ grid resolution) catchment in Denmark. Smaller catchments have been evaluated too – Singh (1997) models a small Indian catchment ($\sim 7km^2$) using MIKE SHE and a $50m$ grid while Koch et al. (2016) applies a $10m$ grid in a MIKE SHE model of a $\sim 0.4km^2$. It should be noted there have been smaller, field-scale, studies that have used finer resolutions – Rujner et al. (2018) evaluate a $\sim 307m^2$ area with a $0.2m$ grid resolution.

It is worth highlighting the dependence of physics-based models on the quality of input data – Duong et al. (2016) found empirical models out-performed a physically based model (SWAT) when simulating runoff in a catchment in central Vietnam and cited this as cause.

The middle ground (between empirical and physics-based hydrological models) is populated by conceptual structures. Beven et al. (2015) states these typically use a series of interconnected stores which are filled and depleted by those hydrological processes that are 'believed to be of importance' (e.g. evaporation or infiltration). As a result, there are multiple established models, each with varying degrees of 'conceptualisation', that have been used to characterise catchment-scale response. One example is the HBV model developed at the Swedish Meteorological and Hydrological Institute (Bergström, 1991; Bergström and Forsman, 1973). Grillakis et al. (2010) evaluated the ability of this model to characterise flash flood response in several catchments ($104km^2$ to $645km^2$) and observed its very strong predictive power. It also been applied at a small catchment scale (Rodriguez Suarez et al., 2014). As has Dynamic TOPMODEL, another established conceptual model (Beven and Freer, 2001). For example, Liu et al. (2009) uses it to characterise the response from a $285km^2$ catchment in Luxembourg.

The principal benefit of conceptual models is that they capture the dominant hydrological process in a parametrically and computationally efficient manner. However, Kavetski et al. (2006) points out that this means parameters cannot be informed directly from measurements, and must be inferred from a calibration procedure (e.g. by comparing the output hydrograph with that observed). Beven et al. (2015) argues that another weakness of conceptual models is that they inevitably contain 'thresholds' that determine behaviour (e.g. at the point a soil store becomes full, rainfall is transferred to surface storage). This lack of 'smoothness' is a problem when using differential equations to describe transfer mechanisms between storage (i.e. computational stability of a solver). Despite this, these models remain an extremely common method for building a catchment-scale response.

Hydrological models can also be defined as 'lumped', 'semi-distributed' or 'fully distributed'. Moradkhani and Sorooshian (2008) defines lumped models as when "the entire river basin is taken as one unit where spatial variability is disregarded". On the other hand,

Table 3.1 Catchment Scale Hydrological Models

	Empirical	Conceptual	Physics-based
Lumped	**ReFH model** **IHACRES** (Dye and Croke, 2003)	**Stanford Watershed Model** (Crawford and Linsley, 1966) **PDM** (Akter et al., 2018)	
Semi-Distributed	**Water Balance Model** (Collick et al., 2009)	**D. TOPMODEL** (Page et al., 2007) **HBV** (Rientjes et al., 2013)	**SWAT** (Bauwe et al., 2019)
Fully Distributed		**HBV** (Beldring et al., 2003; Wrede et al., 2013)	**SHETran** (Janes et al., 2017a) **MIKE SHE** (Singh, 1997)

Arabi et al. (2005) states that distributed models are able to represent spatial variability using 'sub-units' where homogeneous properties are assumed for each. Fully distributed models typically use grid squares as sub-units, whereas semi-distributed models define areas of hydrological similarity using known catchment properties (e.g. land use, soil type etc.).

Table 3.1 gives examples of models and how they have been used in peer-reviewed catchment-scale modelling studies. The table illustrates the breadth in potential approaches to characterising catchment response using hydrological models

Wagener (2007) notes that although models can be categorised in the manner shown in Table 3.1, most models have degrees of complexity and any single classification is perhaps not correct – this is particularly true for physics-based models, which often have a degree of conceptualisation. Similarly, single models can be applied with different levels of spatial distribution. For instance, the Krysanova et al. (1999) details studies on several different catchments with different iterations of the HBV model (HBV-D, HBV-96), each with a different degree of spatial distribution. Menzel et al. (2006) agrees that models with the same conceptualisation can be applied with different regionalisation strategies (and this is shown with the HBV model appearing twice in Table 3.1). So while the table necessitates discrete classification, there are really degrees of conceptualisation and spatial distribution.

3.3.1.2 Hydraulic Models

Catchment response can also be characterised using hydraulic models. Hydraulic models typically solve a version of the physically-based St. Venant's equations (or Shallow Water Equations) to route flow across open surfaces. This is usually achieved with either a 1D, 2D or a coupled 1D/2D approach (Lin et al., 2006a; Tayefi et al., 2007). The equations are solved for each calculation node in the domain, meaning they are distributed models (Felder et al., 2017). Calibration of both forms of catchment modelling (i.e. 1D and 2D) often uses gauged data (Domeneghetti et al., 2012) although inundation extents have also been used (Hall et al., 2005; Horritt and Bates, 2002). However, input data requirements vary for each – 1D models generally require cross sectional geometric and roughness data (and prescribed boundary conditions).

In small catchments with highly dendritic drainage patterns, 1D models require significant cross section survey data and digitization (Choi et al., 2015; Liu et al., 2017). Sufficient data can be hard to obtain and so 1D models often use simplified or parameterised sections (Mejia and Reed, 2011). For instance, Metcalfe et al. (2017) assumes highly idealised uniform cross sections to inform a 1D river model across a $\sim 30km^2$ catchment. There are also examples of 1D studies relying on available data – Saleh et al. (2013) uses the 1D solver in HEC-RAS to study 89km of river reaches using 20 cross-sectional data points. Pasquier et al. (2019) gives another example of using HEC-RAS 1D, modelling a $260km^2$ area in the Norfolk Broads using 1D sections (derived from DEM data) every $30-50m$. Other well known models used for large scale 1D hydraulic modelling include (1) Flood Modeller (formerly iSIS) from Jacobs (formerly CH2M); (2) Infoworks (from Innovyze and discussed later in the thesis) and (3) Mike Hydro (formerly Mike 11) from the Danish Hydraulic Institute (DHI) (Marjoribanks et al., 2014; Pappenberger and Beven, 2004). Examples of Mike Flood being used include Jiang et al. (2019), which modelled a $433km$ river reach with cross sections approximately $20km$ apart to minimise computational requirement or Omai and Nyandwaro (2013) which modelled a $\sim 25km$ reach with 11 cross sections in Mike 11. It should be noted that the upstream boundary conditions for these 1D hydraulic models are typically informed by upstream hydrological rainfall-runoff assumptions (see section 3.3.1.3 for model coupling discussion).

An alternative hydraulic method for characterising catchmment-scale river flows is to use a purely 2D model. Along with prescribed boundary conditions, the minimum requirements for a 2D hydraulic model are topography data and spatially distributed roughness values

(Afshari et al., 2018). For 2D models, DTMs are often used to inform river bathymetry and floodplain morphology (Abdullah et al., 2012). Such methods are reliant on factors such as the DTM's vertical accuracy (Oubennaceur et al., 2018) and spatial resolution (Alho et al., 2009; Savage et al., 2016; Vojinovic et al., 2011). There is also typically a higher computational requirement (Lin et al., 2006a). Despite this, there are many studies that have used this method. For instance, the EA's flood zone mapping in England and Wales was informed by the purely 2D JFLOW model (Bradbrook, 2006). HEC-RAS's relatively new purely 2D model has also picked up traction - Hankin et al. (2019) uses it to characterise river flow in a $15km^2$ catchment in Cumbria. In this case, the upstream boundary condition was informed by a hydrological model. Rangari et al. (2019) simulates response with HEC-RAS 2D for a $47km^2$ urban catchment in Hyderabad, where the upstream input is rainfall falling directly onto the catchment (a 'rain on grid' approach). Another commonly-cited model is TUFLOW (a pure 2D solver) – an example of its use is given by Al-Mamoon et al. (2016), who modelled response from an urban $7.3km^2$ catchment in Qatar (again with a 'rain on grid' approach).

Teng et al. (2017b) provides a comprehensive review of both 1D and 2D hydraulic models, the characteristics of their solvers and an evaluation of wider properties.

3.3.1.3 Coupled Approaches

Zischg et al. (2018) points out that in recent years there has been a significant increase in the coupling of models to create a 'cascade' of numerical replications of environmental domains, particularly in characterising catchment-scale response (Felder et al., 2017; Schumann et al., 2013; Thompson et al., 2004).

To answer the central research question this 'cascading' approach would need to include a (1) rural rainfall runoff routing leading to (2) in-channel routing of catchment flows downstream to (3) an urban drainage system (including pipe flow). The form of coupling between models within this cascading approach can be classified as either 'tight' or 'loose' and has been shown to impact solver solutions (Yu, 2005). A loose coupling between different modelling tools can be considered as a 'one-way filter' and can cause continuity errors (Betsholtz and Nordlof, 2017). Therefore, with loose couples, the location and behaviour at model boundaries is an important consideration. Tight couples do allow feedback, meaning downstream water conditions can affect the response of models higher in the cascade. Integrated models avoid the need for coupling by using multiple solvers to numerically represent different domains within a catchment (Rust and Venn, 2018).

One of the most established form of couplings used to model catchment response is MIKE SHE with Mike Hydro (formerly Mike 11) (Chalkidis et al., 2016; Clilverd et al., 2016; Liuxin et al., 2015; Sandu and Viirsta, 2015; Zhang et al., 2015). This is partly because a tight coupling is possible – ‘river links’, defined by the MIKE SHE grid, create lateral inputs for channel flow in Mike Hydro, while reverse flows are defined using the channel water levels at predetermined ‘H-points’ (Sandu and Viirsta, 2015). There are also numerous instances of Mike SHE being coupled with Mike Urban (Locatelli et al., 2017; Thorndahl et al., 2016). It should be noted that in November 2019 Mike Urban was decommisioned and replaced with Mike Urban+ in early 2020, which now incorporates a 2D overland solver.

Dynamic TOPMODEL has been coupled with both JFLOW (Hankin et al., 2017) and HEC RAS (Hankin et al., 2019).

When coupling between MIKE SHE and MIKE Hydro, the river channel runs along the edges of the hydrological model’s grid, meaning accuracy of the spatial representation of the channel is dependent on the grid’s resolution (Graham and Butts, 2005)

3.3.2 Numerical Replication of NFM

As depicted in section 2.2, there are many different forms of NFM intervention. Alongside this, section 3.3.1 shows there are many different tools with which to model the underlying hydrological system at a catchment scale. Therefore, a model’s ability to represent NFM is dependent on the type of intervention considered and the consequent ability to parameterise appropriate perturbation within the considered transfer mechanisms. Table 3.2 gives examples of when different modelling structures have been used to model interventions’ impact on flow. This highlights the range of potential approaches but also that the same form of intervention can be represented by different perturbations of model boundary conditions and parameters.

The nature of this perturbation is further complicated by two factors. First, the nascent physical evidence base (discussed in section 2.2) means interpretation of the literature can be subjective (e.g. studies in different geographical locations, different local circumstances etc.). Secondly, as discussed in section 3.3.1, nearly all models introduce a degree of conceptualisation in their representation of the hydrological system (incorporating parameters that are not physically measurable). Therefore, any representation of a intervention within such a model structure requires a degree of subjectivity.

While some hydraulic models have been used to represent increased infiltration (see Chappell et al. (2018) given in Table 3.2), this does not happen often because processes such as infiltration and evapotranspiration are represented as abstraction flows (whereas hydrological models can represent such processes with a physical or conceptual basis). Interventions reducing conveyance through the system have been implemented in both hydraulic and hydrological models. With hydraulic models, this can be achieved through head discharge relationships (Thomas and Nisbet, 2012) or using increased flow resistance

Table 3.2 Representation of Natural Flood Management Interventions in selected hydrological models

	Form of NFM Intervention		
	Increasing Infiltration	Reducing Conveyance	Increasing Storage
1D Model		**In-channel woody debris** (Leakey et al., 2020)	**Floodplain reconnection** (Swiatek, 2012)
2D Model	**Tree Planting** (Chappell et al., 2018)	**In-channel woody debris**(Rasche et al., 2019)	**River remeandering** (Poulsen et al., 2014)
1D-2D linked		**Riparian Woodland** (Thomas and Nisbet, 2007)	**Floodplain reconnection** (National Trust, 2015)
Empirical	**Land-use changes** (Bulygina et al., 2011)	**Arable land management** (Wilkinson et al., 2013)	**Offline storage** (Nicholson et al., 2020)
Conceptual	**Tree Planting** (Rodriguez Suarez et al., 2014)	**In-channel woody debris** (Odoni and Lane, 2010)	**RAFs** (Metcalfe et al., 2018)
Physics-based	**Land-use changes** (Wheater et al., 2008)	**Moorland grip blocking** (Geris et al., 2010)	**Floodplain reconnection** (Clilverd et al., 2016)

(typically Manning's n) as a proxy (Dixon et al., 2016). In hydrological models, the way this is accomplished is through increased resistance (Odoni and Lane, 2010) or alterations to sub-surface transfer mechanisms (Geris et al., 2010)). However, hydraulic models, being both distributed and physically-based, offer more confidence in the representation of created storage through hypothetical geometric alteration (Hankin et al., 2019) (although Metcalfe et al. (2018) does this indirectly in a conceptual hydrological model through alterations in residence times within HRUs). This range in abilities in representing different perturbations of the catchments' hydrological systems lends further support to the argument for using a coupled modelling approach (discussed in section 3.3.1.3).

It is not the purpose of this research to contribute to the physical evidence base, or to offer fresh numerical interpretation of the physical studies to date. Therefore, the modelling methodology will rely on precedent and make use of previous numerical representations of interventions.

3.3.3 Characterisation of Drainage Performance

The third characteristic used to evaluate potential methodologies applies to the drainage models and their ability to characterise their response in a way fit for purpose to answer the research question.

There are instances in the literature of overland hydraulic models accounting for subsurface drainage through a reduction in net rainfall – for example Vercruysse et al. (2019) in a source-to-impact analysis of surface flooding with CityCAT in Newcastle city centre. Such a methodology was not deemed suitable for this research, given the focus on behaviour of outfalls and subsequent (potential) surcharging of the contributing urban system. Therefore, a separate drainage model needs to be incorporated into the coupled model cascade (see section 3.3.1.3 above).

One of the mechanisms used to determine outfall behaviour in determining model behaviour is the 'inundation threshold' of each (defined in section 2.3.1). Establishing this threshold requires the amalgamation of geometrical data from both the urban watercourse and the drainage system. The inundation threshold is constant and so the 'inundation duration' (again see section 2.3.1) could then be defined by modelling the urban watercourse alone.

While the inundation duration is a demonstrable metric with which to evaluate upstream NFM impact, it does not give any understanding of the consequent response of the surface drainage system. Capturing this requires explicit modelling of the drainage under both free draining and surcharged flow states. The ability of different models to this varies and so the properties of four different approaches will now be reviewed.

- **Environmental Protection Agency's Storm Water Management Model (SWMM)**
  Background: The well-established solver (for the St Venant's equations with a finite difference solver) is a semi-distributed rainfall runoff drainage model, but does not offer any capability for characterising open channel flow conditions (Burger et al., 2014).
  Representation of Surcharged Flow: Surcharged flow is simply stored at upstream manholes until it can be routed (Zaghloul and Abu Kiefa, 2001). If applicable, a hydrograph of discharge to the surface is available, but no flooding extents. The model is well-established in modelling surcharged flow (Hooshyaripor and Yazdi, 2017; Kim et al., 2018)
  Representation of Outfall Inundation: As SWMM does not incorporate open channel flow, this could only be incorporated by manipulating downstream boundary conditions accordingly. However, this approach would have certain drawbacks. Firstly, it would introduce a small continuity error – it takes no account for flow entering the urban

watercourse from the surface drainage system contributing to inundation of outfalls downstream. Secondly, such a method would require a more intricate translation of water levels within the hydraulic river model to determine boundary conditions for the contributing drainage model.

- **Infoworks ICM**
  Background: This is a commercial model from Innovyze. Integrated pipe and open channel flow is solved using the St. Venant Equations.
  Representation of Surcharged Flow: Representation of surcharged flow relies on the Priessman slot approximation.
  Representation of Outfall Inundation: This can be represented as the model integrates open channel flow and sub-surface drainage through outfall nodes.

- **City Catchment Analysis Tool (CityCAT)**
  Background: This tool has an academic background, having been under development at Newcastle University. It has primarily been used to characterise overland flow (using full 2D shallow water equations) in urban areas (Glenis et al., 2018; Pregnolato et al., 2016; Vercruysse et al., 2019), although a pipe flow module also exists (Bertsch et al., 2017).
  Representation of Surcharged Flow: This is one of the few models that does not use the Priessman slot approximation, instead using a conservative form of the Alievi Equations based on the compressible Euler equations.
  Representation of Outfall Inundation: Theoretically possible but no relevant literature found.

- **Mike Urban**
  Background: This is an established commerical model from DHI which combines various solver engines (including Mike 1D and Mike Flood and a SWMM solver) to achieve an integrated modelling approach. It should be noted that in early 2020 Mike Urban was replaced with Mike Urban+ which also incorporates 2D modelling.
  Representation of Surcharged Flow: Representation of surcharged flow relies on the Priessman slot approximation
  Representation of Outfall Inundation: This can be represented as the model also integrates open channel flow and sub-surface drainage through outfall nodes.

3.3.4 Availability

Section 2.2.4.1 highlighted the prominent role of CMPs in the physical implementation of NFM interventions and how budgetary pressures faced by these organisations have created scepticism over the benefits of using models in NFM evaluation. Conclusions on the central research question will potentially be of benefit to CMPs but only by adopting a modelling approach which is appropriate to their circumstances. Ideally then, any constituent models should be both publicly accessible and without significant computational requirement.

3.4 Outcome of Methodological Review

Section 3.3 laid out four distinct criteria to assist with the methodological review. The abilities of different approaches to fulfil each has been thoroughly explored. The final decision was to use a cascade of models using Dynamic TOPMODEL, HEC-RAS and Infoworks ICM.

A full explanation and justification of this decision, as tested against each of the criteria, is set out below.

1. *Method be suitable for characterising response at a catchment-scale*
   After reviewing the available catchment-scale methods for characterising catchment scale response in section 3.3.1, it was decided that a coupled modelling approach was the most suitable approach.

   A physically-based hydrological model was deemed too data intensive – the catchments studied in this research project must be primarily identified for their issues with downstream surface drainage outfalls, rather than the availability of distributed data. A hill-slope model with a degree of conceptualisation was therefore preferred.

   As discussed in section 3.3.1.2, any hydraulic model incorporated into the methodology 'cascade' to characterise flow in the riparian zone will be fully distributed. As a result, any contributory hydrological rainfall-runoff model will need to at least provide semi-distributed inputs as upstream boundary conditions.

   In summary, the rural hydrological model would ideally be both conceptual and semi-distributed. This meant using a model such as Dynamic TOPMODEL, HBV or OVERFLOW (discussed above).

   The constraining factor for the hydraulic model was the availability of data – there was very little likelihood of a case study catchment (again, chosen primarily for issues with downstream drainage) having sufficient cross-sectional data to inform a 1D model of small, dendritic channel network. Therefore, as section 3.3.1.2 discusses, the options were to use idealised bathymetry or a 2D model. The decision was taken to use the latter and take advantage of the UK's extensive availability of DTM data (through EA and Ordnance Survery (OS) mapping).

   Section 3.3.1.2 gives examples of different 2D models being used to characterise catchment response. There are several aspects of the HEC-RAS solver which set it apart from others (TUFLOW, JFLOW etc.). These aspects include (i) being able to solve both the full shallow flow equations and the diffusive wave approximation (ii) using preprocessing to capture sub-grid topography (discussed in section 3.6) and (iii) the under-utilised HEC-RAS Controller API (application programming interface) which is discussed in section 3.6.1 which makes it more amenable for coupling and also running multiple simulations.

2. *Replication of a range of NFM interventions in the rural environment*

   Section 3.3.2 reviews the multitude of approaches in evaluating NFM numerically (see Table 3.2) and offers further support for using a coupled modelling approach. It also highlights the need for this methodology to rely on precedent. There is a significant body of work (discussed further in sections 3.5 and 3.8) from Lancaster University evaluating the catchment-scale impact of NFM with Dynamic TOPMODEL around the UK. There is also a (more disparate) body of work using HBV (e.g. Rodriguez Suarez et al. (2014)), although much of this is based in Scandinavia (for historical model development reasons). There is a smaller amount of literature behind OVERFLOW (e.g. Odoni and Lane (2010)), as it was only developed about 10 years ago.

   Given hydraulic models solve some form of the shallow flow equations, there is less reliance on model structure when replicating NFM interventions.

3. *Integration of pipe flow and open channel flow within the urban environment*

   Section 3.3.3 summarised the attributes of four well-known models used for characterising drainage flow.

   It was felt that an integrated urban environment (i.e. being able to characterise both open channel and pipe flow) was necessary to properly evaluate how outfall inundation altered the contributing drainages' performance (negating SWMM). While CityCAT offers impressive numerical replication of different flow domains, the solvers require significant computational requirement and the pipe flow module is yet to receive significant evaluation in the literature (or be applied outside Newcastle). The assumptions (primarily the Priessman slot representation of surcharged flow) were accepted as a pragmatic assumption in the methodology. Infoworks ICM was preferred over Mike Urban primarily because the majority of UK water companies hold drainage data within large Infoworks ICM models, meaning a licence would be needed anyway to utilise this data.

4. *Widely accessible and not require significant computational requirement*

   Section 2.4 highlighted the need to adopt a modelling methodology that was based primarily on openly accessible solvers.

   Dynamic TOPMODEL, SHETran, HEC RAS and SWMM are freely available online as discrete solver packages. OVERFLOW (Odoni and Lane, 2010), HBV (Bergstrom,

1992) and CityCAT (Glenis et al., 2018) are theoretically available, but their academic progenies limit wider accessibility. The Mike packages, JFLOW and Flood Modeller are commercial tools and do require licencing.

Dynamic TOPMODEL was preferred over other available hydrological models because it has been implemented as a freely available R package (see section 3.5), which makes code produced within this research easily reproducible.

Admittedly, the methodology has decided to use Infoworks ICM, which requires a commercial licence (although kindly provided by Innovyze for the majority of this research). However, this approach was still deemed suitable as the rural catchment response (and subsequent NFM interventions) is characterised by freely-available models (see section 2.2.4.1 for discussion on the needs of CMPs).

Figure 3.1 diagrammatically presents the role of each of the constituent models within the justified methodology. Having presented this justification of the choice of modelling methodology, each of these constituent tools will now be described in more detail, especially in relation to their particular application to the case studies that will follow.

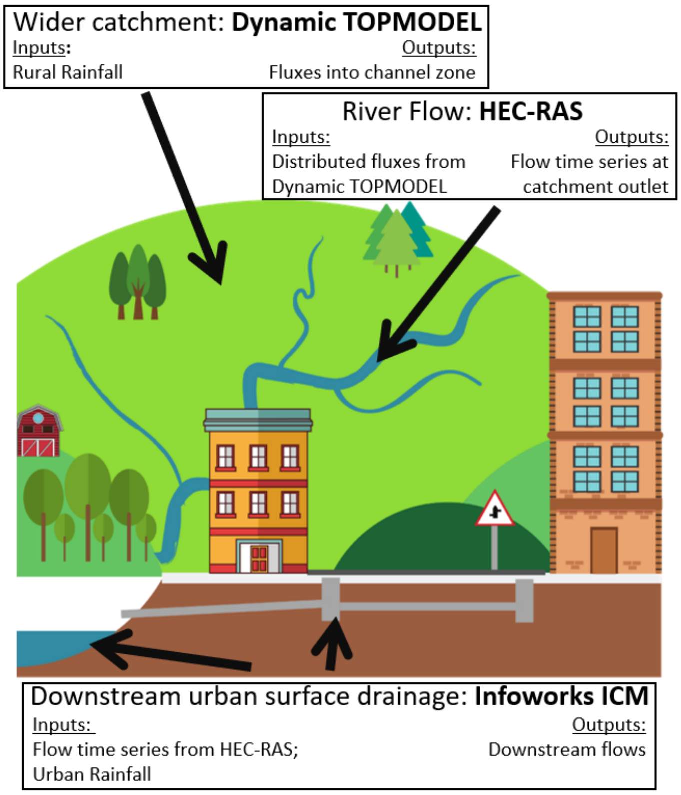


Figure 3.1 Constituent models within the justified methodological procedure

3.5 Dynamic TOPMODEL

Dynamic TOPMODEL is a semi-distributed, semi conceptual hydrological model derived from TOPMODEL (Beven and Freer, 2001; Beven and Kirkby, 1979). Dynamic TOPMODEL is an established academic tool for characterising whole-catchment hydrological response, having been used to evaluate the spatial variability of rainfall (Younger et al., 2009), estimate contaminant transfer (Page et al., 2007) and quantify the impact of NFM (Hankin et al., 2016; Metcalfe et al., 2017). The model structure used throughout this research is freely available online as an R programming package in the CRAN repository[1]. The structure of this implementation is discussed in detail in Metcalfe et al. (2015) and will be briefly summarised here.

The model has two major assumptions:

1. The effective hydraulic gradient within the soil is equal to the topographic slope (i.e. the water table is near to parallel to the ground surface)

2. Transmissivity has an exponential form (i.e. reducing with increased depth) when the soil is saturated at the surface (see Figure 3.3)

One of the primary differences between Dynamic TOPMODEL and TOPMODEL is that the assumption of a steady state water table was replaced by a kinematic solution for subsurface storage and downslope base fluxes (Metcalfe et al., 2015).

The two key assumptions to Dynamic TOPMODEL mean it is best suited to catchments (i) with moderate slopes and (ii) whose response is dominant by shallow soils.

Fundamentally, the model discretises a catchment space into areas that will respond in a hydrologically similar manner (this is shown diagrammatically in Figure 3.2). These areas are termed Hydrological Response Units (HRUs) and are typically defined by topography, but can be additionally discretised using characteristics such as soil type, land use or flow distances (see Figure 3.2 for a diagrammatic representation). This, along with the parametrically parsimonious definition of HRU properties, simplifies computational complexity and reduces run times. The seven primary parameters are described in Table 3.3 and the purpose of each will now be related to the structure of the solver.

The model is conceptual and there are three principal storage types within each HRU - root zone, unsaturated and excess. After initialisation, the code solves these lumped-storage volumes for each HRU in each time step. The rainfall input is added to the root zone storage until the defined limit $s_{rz,max}$. Further rainfall is then added to any available volume in the unsaturated zone before surface excess is generated.

[1]https://CRAN.R-project.org/package=dynatopmodel

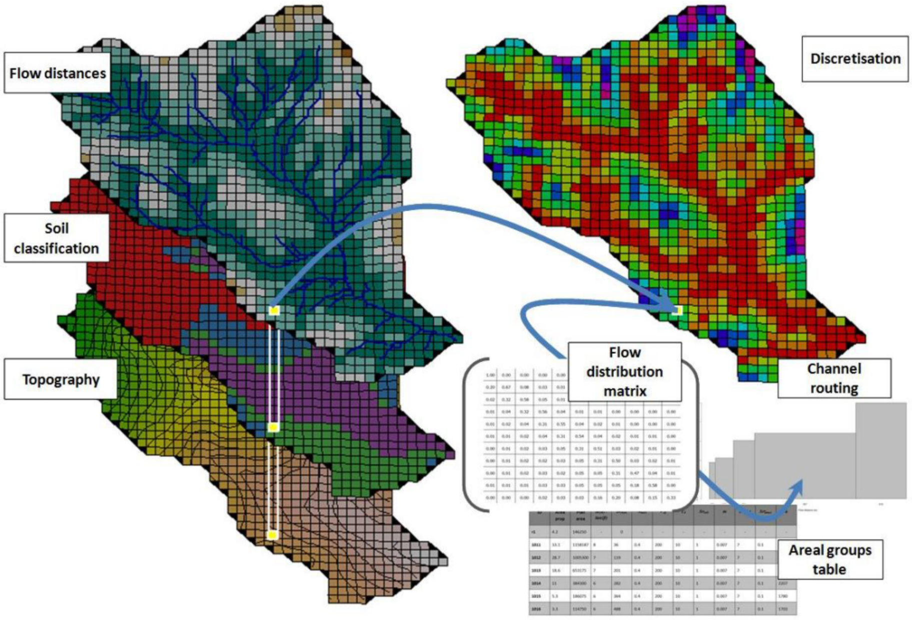


Figure 3.2 Dynamic TOPMODEL Discretisation (with exemplar GIS layers) from Metcalfe et al. (2015)

Evapotranspiration loss for each HRU, E_a, is removed from the root zone storage and is calculated for each time step as:

$$E_a = E_p \times \frac{s_{rz}}{s_{rz,max}} \tag{3.1}$$

where E_p is the potential evapotranspiration and the fraction gives the ratio of the root zone storage filled at the beginning of this time step.

The other form of loss is gravity-induced draining from the unsaturated zone, q_{uz}, into the water table which is calculated as:

$$q_{uz} = \frac{s_{uz}}{sd \times t_d} \tag{3.2}$$

where s_{uz} is the unsaturated zone storage, sd is the storage deficit and t_d is an effective permeability term which reflects the ability of water to drain vertically through the soil.

Once the different storages in each HRU have been calculated, the formulation for horizontal flux begins. This is dependent on the weightings matrix, W, which is constructed by: (i) using the M8 multiple flow direction algorithm (from Quinn et al. (1991)) and (ii) by approximating hydraulic gradient with topographic slope (see main assumptions listed above). The topographical slope is typically derived from a Digital Terrain Model. The

Table 3.3 Primary Parameters for Dynamic TOPMODEL (typical ranges informed by Freer et al. (2004); Metcalfe et al. (2015); Page et al. (2007); Younger et al. (2009))

Parameter	Units	Description	Typical Range
$ln(T_0)$	m^2/h	Lateral saturated transmissivity	$3-12$
m	m	Form of exponential decline in conductivity	$0.0011-0.033$
$s_{rz,max}$	m	Maximum root storage	$0.1-0.3$
$s_{rz,0}$	%	Initial root storage	$80-100$
sd_{max}	m	Maximum effective deficit of saturated zone	0.5
t_d	hr/m	Unsaturated zone time delay	$10-50$
v_{chan}	m/hr	Channel Routing Velocity	$1000-2000$
v_{of}	m/hr	Overland flow routing velocity	$50-150$

weighting matrix takes the form:

$$W_{n,n} = \begin{pmatrix} p_{1,1} & \cdots & p_{1,n} \\ \vdots & \ddots & \vdots \\ p_{n,1} & \cdots & p_{n,n} \end{pmatrix} \qquad \sum_{j=1}^{n} p_{ij} = 1 \tag{3.3}$$

where there are n different HRUs and element p_{ij} represents the proportion of flow from HRU i flowing into adjacent unit j. Elements where $i = j$ (i.e. the elements in the lead diagonal) give the proportion of flow that remains in the same HRU for each time step.

With regards to the subsurface routing, one can apply the principle of continuity to relate the input and output flows into a finite, unsaturated soil volume (i.e. an HRU) as:

$$\frac{\partial D}{\partial t} = \frac{\partial q}{\partial x} - q_{uz} \tag{3.4}$$

where the $\frac{\partial D}{\partial t}$ term describes the rate of *increasing* storage as a result of influx $\frac{\partial q}{\partial x}$ and drainage from the volume into the water table (q_{uz}). Equation 3.4 can be manipulated by incorporating a functional dependency between storage and discharge. The formulation is converted from a partial differential to an ordinary differential using the transmissivity profile and the weightings matrix (Equation 3.3). The exponential decline of the soil's transmissivity profile is defined with the parameters from Table 3.3, as shown in Figure 3.3. The resultant ordinary differential equation is solved using an implementation of the Livermore solver within R.

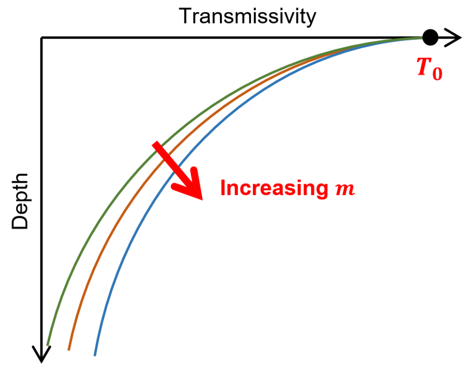


Figure 3.3 A conceptual representation of the exponential transmissivity profile assumed by Dynamic TOPMODEL

Any *surface flux* (obtained once the unsaturated zone fills) is, again, assumed uniform over each HRU and solved by considering continuity:

$$\frac{d\underline{s}}{dt} = q_{in} - q_{out} = \mathbf{A}\underline{v} * \underline{s} - \underline{v} * \underline{s} \tag{3.5}$$

where $\underline{v}$ is a vector containing elements specifying overland flow velocity (v_{of}) for each HRU, $\underline{s}$ is a vector containing the specific excess storage for each HRU, $\mathbf{A}$ is a matrix dependent on the weightings matrix, W, and HRU area. The $*$ denotes element-wise multiplication (of identically-sized vectors). Critically, the surface weightings matrix can be changed to reflect overland connectivity.

Furthermore, specific excess storage height can be defined, ex_{max}, above which another, separate weightings matrix can be defined. This can then be used to define spillways and overland flow channels within the catchment.

The flow is routed (either overland or sub-surface) down the catchment slope to become inputs for river channels. The CRAN package implementation of Dynamic TOPMODEL uses a highly simplified channel routing scheme based on a linear network width function. This uses a simple 'time-delay histogram' which proportions all flow entering the channel (based on the geographical layout of the river network) and assuming a fixed channel velocity, v_{chan}. This routing scheme further minimises the computation requirement of the model and Beven (1979) justifies it empirically as a reasonable approximation in small catchments (up to $\sim 10km^2$).

However, for the purposes of this research, this simple channel routing module has been replaced by coupling in a HEC RAS 2D model. This has several benefits. Firstly, the distributed hydraulic representation of channel flow captures the sequencing and phasing of tributary responses at channel confluences (known to have significant impact on downstream flow (Pattison et al., 2014)). This is particularly important given the distributed nature of NFM interventions. Secondly, incorporating the hydraulic model enables justifiable representation of NFM interventions within the riparian zone (as discussed in section 3.8). Finally, with the original routing model, Dynamic TOPMODEL produces a single catchment output point which, to allow calibration, is typically a gauged river section. However, to incorporate the subsequent urban drainage model (which, for certain case studies, was upstream of these river gauges), a more distributed approach to characterising river flow was necessary.

3.6 HEC RAS

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) is a freely available, established tool from the US Army Corps of Engineers[2]. It has been applied for various purposes including flood modelling (Kumar et al., 2017a), storm surge interaction (Teng et al., 2017a) and sediment transport (Haghiabi and Zaredehdasht, 2012). The solver traditionally has been purely 1D but has recently incorporated a 2D module (allowing both pure 2D and coupled 1D/2D approaches) (Afshari et al., 2018).

This methodology uses the pure 2D solver to characterise the in-channel flows (for reasons justified in section 3.3.1.2). The details of the 2D solver are discussed in (US Army Corps of Engineers, 2016) but will be summarised in general terms here.

The 2D shallow flow equations take the form of the continuity equation (Eq. 3.6) and the momentum equation (Eq. 3.7 and 3.8). The continuity equation can be expressed as:

$$\frac{\partial H}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \tag{3.6}$$

where u and v are the velocities along the Cartesian planes (x and y directions), H is water surface elevation and t is time.

The (vertically averaged) momentum equations can be expressed as:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial H}{\partial x} + v_t\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - c_f u \tag{3.7}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial H}{\partial y} + v_t\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - c_f v \tag{3.8}$$

where g is gravity, v_t is the horizontal eddy viscosity coefficient and c_f is the bed surface friction coefficient.

On the left hand side of Equations 3.7 and 3.8 are the convective equation term and the two unsteady acceleration terms. On the right hand side are the forces acting on the fluid: hydrostatic pressure, eddy turbulence diffusion and bed friction.

Although the HEC RAS can solve the full shallow flow equations, this research used the diffusive wave approximation. The assumption means that the unsteady acceleration, advection and turbulence terms of the momentum equation are disregarded. In other words, flow movement is driven by hydrostatic pressure and bed friction alone. This is a commonly used assumption as it allows for a more rapid and stable solution (Bradbrook et al., 2004). It

[2]https://www.hec.usace.army.mil/software/hec-ras/downloads.aspx

was also considered a reasonable assumption within this research in that HEC RAS is being used to characterise flow moving across large, moderately sloping areas.

Before solving fluxes using the equations described above, HEC RAS applies several pre-processes to improve computational efficiency and stability. Within the 2D domain mesh, every cell is assigned hydraulic property tables based on the (typically finer resolution) underlying DTM and roughness data. These contain a water elevation-volume relationship for each cell, meaning larger cell resolutions can be used while also capturing the detail of the terrain (rather than assuming a flat bottomed cell). The hydraulic property tables also include relationships for each cell face – elevation against wetted perimeter, area and roughness (all derived from the underlying DTM). HEC RAS then computes conveyance at these elevations. The model linearly interpolates between points on this elevation-conveyance relationship. However, if two adjacent conveyance values are not within 2% of each other, another elevation is computed at the centre point. This method reduces error in the conveyance curves and increases the computational stability of the solution. These conveyance values are used to inform the diffusive wave approximation of the fluxes moving between adjacent cells in the 2D mesh.

This preprocessing of individual cell properties allows larger cell sizes to be used, while still accounting for the underlying terrain. Furthermore, the case study catchments are moderately sloping (e.g. no waterfalls or significant shocks). These factors allows the use of a (computationally pragmatic) coarse 2D mesh with an approximate resolution of 30m and a computational time step of 15 seconds. The stability of solution was ensured using the guidelines given for the Courant number (under the diffusive wave equations) in the 'HEC RAS 2D Modeling User's Manual' (Brunner, 2016), given as:

$$C = \frac{v \times \Delta t}{\Delta x} \leq 2 \tag{3.9}$$

The upstream boundary inputs are informed by flows from Dynamic TOPMODEL (using coupling process described in section 3.7). The downstream boundary is a normal boundary condition (with a slope determined by DTM topography) at the downstream gauging station, perpendicular to the direction of flow.

Together, Dynamic TOPMODEL and HEC-RAS characterise the whole-catchment response. While being fit for purpose, there are inevitable assumptions in both their structure and usage within this methodology. The resultant uncertainties are discussed in detail in section 3.12.

3.6.1 HEC RAS Controller

One of the key justifications for using HEC RAS (discussed in section 3.4) is the 'HEC RAS Controller'. The Controller is an API (application programming interface) and includes a toolbox of programming modules which allow automation of HEC-RAS. It is also a Component Object Module (COM), meaning it can be called through any program able to read COM DLL (Dynamic-Link Library) (e.g. Excel VBA, Matlab or Python) (Goodell, 2014).

With sufficient computational power, automation of HEC RAS provides the ability to conduct sensitivity analyses for calibration and subsequent scenario testing. Goodell (2014) details many of the available commands available but despite this, there is extremely little evidence of the HEC RAS Controller's use in peer-reviewed literature.

Leon and Goodell (2016) offers an overview of fundamental scripts through Matlab while Dysarz (2018) does the same for Python. Loi et al. (2019) couples SWAT (an established hydrological model) with a 1D HEC RAS model using the Controller to statistically evaluate real time flood forecasting at a catchment scale. Jonoski et al. (2018) examines the role of operated flood storage areas using a 1D river and the Controller. Dysarz et al. (2019) uses the Controller to examine future scenario river flows (again using a 1D model). Taken together, these sources form the majority of the available peer-reviewed work utilising the API and demonstrate how the Controller's value has only recently gained attention in academic literature. Although applied to different forms of problem, there has also been a focus to date on using the API to govern the 1D HEC-RAS solver. Not only does this research add to the emerging body of knowledge behind using the Controller (primarily through online repositories created to support the published aspects of the work), it also extends it by applying the modules to a 2D study.

Ideally, the Controller would have been run using the R language to mirror that of Dynamic TOPMODEL and provide an elegant workflow. However, the ability to work with COMs within the R language is extremely poor. Moreover, there are no previous examples of using the Controller in R, meaning there is no information on the detailed structure of commands to run HEC RAS modules. Therefore, the 2D module functions and subroutines were accessed through Matlab (explained examples of these modules and scripts are given in Appendix X). Figure 3.4 presents the overall workflow for the constituent models characterising the rural response for each case study catchment.

3.7 Coupling of rural models

Dynamic TOPMODEL characterises the response of the wider catchment in order to provide the upstream boundary input for the HEC RAS 2D river model (justified in section 3.3). This approach has been largely unrecognised, having been used only once by Hankin et al. (2019) (some authors of that paper were involved in the development of Dynamic TOPMODEL). One of the principal contributions of this research is the detail and evaluation provided on this coupled modelling methodology. In the literature, coupling of Dynamic TOPMODEL and HEC-RAS remains cryptic and under-utilised, despite together offering a freely accessible, data-efficient catchment-scale modelling approach based on well established models with significant potential for multiple simulations and scenario testing. The coupling strategy used in this research is now explained below.

First, a spatial buffer of 20m width was created around each individual river reach using GIS software (the number of reaches was therefore dependent on the case study catchment in question). These were then 'burnt' into the Dynamic TOPMODEL discretisation (defined in general terms in section 3.5 and with regards to calibration in section 3.10). The result was that each river reach had a surrounding HRU. Fluxes passing into these 'river reach HRUs' were then extracted from Dynamic TOPMODEL for the duration of each simulation run.

An Excel Macro was developed, incorporating elements of the HEC-DSSVue Excel plugin[3](a freely available tool) and other VBA script, to automate the process of converting these Dynamic TOPMODEL fluxes into DSS files (the input file structure required by HEC-RAS). This script is given (and annotated) in Appendix X. This workflow (depicted in Figure 3.4) allowed many simulations to run in Dynamic TOPMODEL to be provide input fluxes for a fully distributed HEC RAS model without the (prohibitively) laborious translation of data.

The upstream boundary conditions for the HEC RAS model were located along the 20m reach buffers originally burnt into Dynamic TOPMODEL. Each provided a (reach-averaged) input hydrograph to the 2D hydraulic model.

3.8 Representation of NFM Interventions

This research incorporates two forms of NFM intervention across each of the three case study catchments: (1) cross-slope tree planting and (2) in-channel large woody debris. The extents of these interventions vary with the catchment case studies (Chapters 5 to 7), but their numerical representation remains similar. This allows comparison of their effect in Chapter

[3]https://www.hec.usace.army.mil/software/hec-dssvue/plugins.aspx

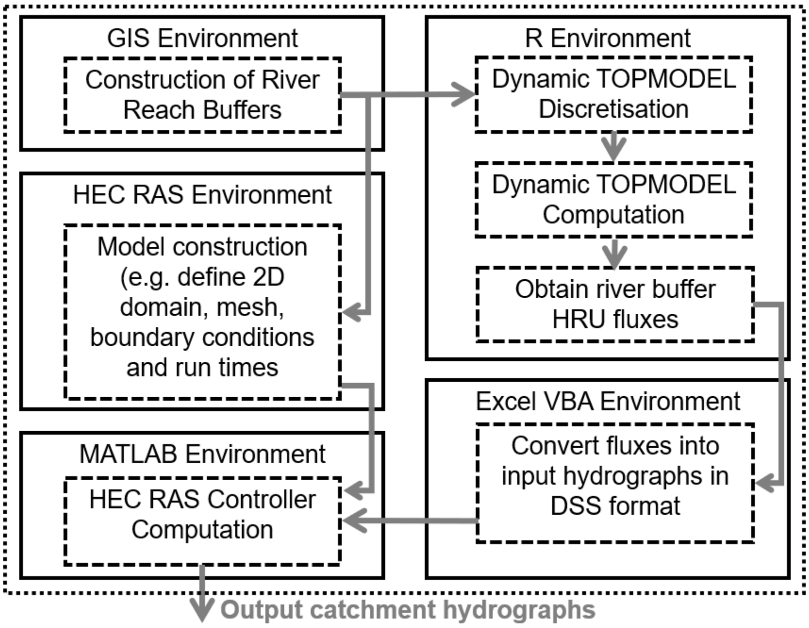


Figure 3.4 HEC RAS Controller Workflow

9. Between them, they achieve the three principal mechanisms of NFM interventions (ie. increase infiltration, reduce conveyance and introduce storage).

3.8.1 Tree Planting

The tree planting intervention was represented in Dynamic TOPMODEL with slight alterations of calibrated parameters in the hydrological model. These shifts are given in Table 3.4. The justification and implications of each parameter shift will now be discussed.

The parameter T_0 (or 'limiting transmissivity') is a measure of the maximum saturated lateral transmissivity in the soil (i.e. the integral of the hydraulic conductivity profile from bedrock to the ground surface). There have been numerous physical studies in temperate climates investigating the role of tree planting on hydraulic conductivity. For instance, Chandler et al. (2018) found significant differences when comparing lateral conductivities of soils underneath grazed pasture ($32 mm/hr$) to ungrazed Scots Pine ($1239 mm/hr$) and ungrazed sycamore ($379 mm/hr$). These findings also highlight the differing role tree species can have of on underlying soil permeability. Chandler and Chappell (2008) found that the saturated hydraulic conductivity 3 metres from individual oak trees increased by a mean average factor of 3.4 (when compared with surrounding grassland) and provided a review of comparative studies. Hankin et al. (2016) updated this review with studies finding factors (between hydraulic conductivity under trees when compared with nearby pasture) of between

Table 3.4 Representation of tree planting within Dynamic TOPMODEL (informed by (Hankin et al., 2017))

Parameter	Factor	Justification
$ln(T_0)$	$\times 1.5$	Slight increase (to unlogged value) in saturated soil conductivity
m	$\times 1.2$	Slight decrease in steepness of the decline in soil conductivity
$s_{rz,max}$	–	
$s_{rz,0}$	$\times 0.99$	Slight decrease in antecedent soil moisture to reflect higher preceding evapotranspiration losses
sd_{max}	–	
t_d	–	
v_{chan}	–	
v_{of}	$\times 0.75$	Decrease in overland flow to reflect heightened surface roughness

1.8 and 8. Hankin et al. (2016) then used this review to inform a suggested parameter shift to T_0 of between 1.5 and 2.5 to reflect tree planting. A shift of 1.5 was used in this study.

The m parameter is used to define the rate of exponential decline in conductivity through soil depth, low values (such as those found in the calibration – see calibration range and final calibrated value in Table 3.4), indicate a very steep decline in underlying soil conductivity. There is physical evidence that areas of tree planting will ‘soften’ the reduction in soil conductivity. For instance, Peskett et al. (2020) uses physical measurements of ‘forest strips’ in a Scottish catchment to demonstrate deepening of the active hydrological response. This built on work performed in the same catchment by Archer et al. (2013), which found that tree rooting systems play a significant role in controlling hydraulic conductivity of soil and highlighted “the significantly higher infiltration and sub-soil K_{fs} [saturated hydraulic conductivity] under afforested areas in contrast to the heavily grazed grasslands.” Both Schwärzel et al. (2012) and Jost et al. (2012) offer further evidence supporting the role that root zones have in altering the conductivity profiles of underlying soils in temperate climates. Coulthard et al. (2000) used the m parameter in TOPMODEL to model the impacts of tree planting in the Cam Gill Beck (Yorkshire), assigning values of 0.005, 0.01, 0.015 and 0.02 to ‘sparse’, ‘medium’, ‘dense’ and ‘very dense’ vegetation scenarios. Similarly, Coulthard and Van De Wiel (2017) use this method in an iteration of TOPMODEL when evaluating the impact of land use change on sediment loads in the Swale catchment. Given both the physical evidence and this precedent, this study uses a modest factor of 1.2 to slightly increase the m parameter (as shown in Table 3.4).

The third parameter used to define the impacts of tree planting is v_{of}, the velocity of overland flow, which can be expected to be reduced by trees increasing surface roughness. There are few physical studies comparing roughness (typically using Manning's n) of grassland and afforested areas. Chow (1959) ascribed floodplain grassland with $n = 0.035$ and dense forest with a range of $n = 0.1 - 0.2$. Medeiros et al. (2012) gave closer ranges of $0.013 - 0.05$ for grassland and $0.03 - 0.061$ for forest (again measured on floodplains). The increase in roughness created by forested areas is a commonly found assumption in modelling (Thomas and Nisbet, 2007), although it is recognised that more studies are needed to provide more confidence in values (Nisbet et al., 2011). From the physical studies, Hankin et al. (2016) puts forward a suggested reduction in V_{of} of between 0.75 and 0.5 (a factor of 0.75 is used here).

The final alteration made to reflect the representation of tree planting is srz_0, the initial root zone storage deficit (as a percentage of the volume filled). The structure of the model is such that evapotranspiration losses are removed from this storage volume. Owing to the higher degree of losses through preceding evaporation from trees, this parameter value can reasonably be expected to be slightly lower to represent the intervention. Several physical studies have shown that the presence of trees creates drier topsoils during rain free periods (Katul et al., 1997; Özkan and Gökbulak, 2017). However, Geris et al. (2015) highlights the dominance of soil properties (over variable landcover) when evaluating dynamic storage losses to evapotranspiration in a Scottish Highlands catchment. Brinkmann et al. (2019) also argues that these losses (similarly to the other phenomena discussed above) are species specific. This study reduces the initial storage volume by 1%.

3.8.2 In-channel woody debris

The other intervention modelled in this research is in-channel large woody debris, which is used to increase hydraulic resistance within the channel zone by creating a throttling impact during larger events (Bornschein and Pohl, 2018). The backwater effect creates small in-channel storage, as well as encouraging flows into the riparian zone. There are many terms for such interventions – large woody debris (Shields et al., 2004), engineered log jams (Bennett et al., 2015) and woody debris jams (Manners et al., 2007). Numerous physical studies have investigated their hydraulic impact, both in flumes (Bocchiola et al., 2006; Young, 1991) and in-situ (Dixon and Sear, 2014). There have also been several studies investigating their multiple benefits, including restoration of biodiversity (Thompson et al., 2018) and effecting sediment processes (Brooks et al., 2006; Shields et al., 2006). Extensive coverage of the intervention through a river network is regarded as necessary to have an effect on catchment scale response (Thomas and Nisbet, 2012).

There has been much discussion about how to model such structures. One approach is to model woody debris using head discharge relationships (or hydraulic control structures) (Leakey et al., 2020). Another, commonly used, method is to alter the underlying roughness as a proxy (typically a Manning's n parameter) (Adams et al., 2019; Curran and Wohl, 2003; Dixon et al., 2016; Odoni and Lane, 2010; Rasche et al., 2019; Thomas and Nisbet, 2007). This is the method used here. After calibration of the HEC RAS model, all areas designated for large woody debris have their Manning's n value increased to 0.1. This is conservative (i.e. smaller) compared with other studies (Addy and Wilkinson, 2019), but does not account for factors such as (i) topographical slope (ii) contributing drainage area (iii) channel type (eg. straight, sinuous, meandering) or (iv) bed material. It also does not deviate with flow conditions. Large woody debris, however, can be considered to have an immediate effect (unlike tree planting). Overall, given the volume of significant and related previous work, adjusting Manning's n parameter was considered to be the most suitable way to model large woody debris within the scope of this research.

Within each of the case studies the extents of each intervention will be discussed individually. However, in all three, a GIS study was used to identify appropriate reaches for implementation. This was done for two reasons. Firstly, implementation is not restricted to areas of natural woodland – artificial or engineered structures have also been widely recognised in the literature (Addy and Wilkinson, 2016; Hygelund and Manga, 2003; Keys et al., 2018; Manners and Doyle, 2008). Secondly, the intervention was only applied in areas at least 50m from any infrastructure (e.g. bridges, buildings or culverts etc.). The reason for this was to take account of the results from several studies conducted on the movement of woody debris in channels (Curran, 2010; Dixon and Sear, 2014) and the potential for detrimental impact on downstream infrastructure (Pagliara and Carnacina, 2011).

Further details on the extent and impacts of each of the interventions will be provided in the case study chapters.

3.9 Urban Environment

3.9.1 Infoworks ICM and coupling with rural model

As justified in section 3.3.3, this methodology uses an Infoworks ICM model to simulate the response of the downstream urban area. Infoworks ICM is a commercial tool from Innovyze that allows integrated representation of multiple types of water flow within a catchment. It is only available under licence (limited by either 1D nodes or 2D mesh elements). The third case study (in Todmorden – see Chapter 7) was carried out in conjunction with Yorkshire Water (the local water company) who, along with Innovyze, enabled access to a full Infoworks ICM licence for all three case study areas in the research project.

In a 1D domain, ICM uses the implicit 'Preissmann weighted 4-point scheme' (Preissmann, 1961) in order to approximate the St. Venant equations. This allows solutions to be obtained over unequal distance steps (necessary for open channel flow) and unequal time steps (helpful for unsteady flow). The finite difference solver uses the Newton-Raphson method. The transition of free-drainage within surface water drainage pipes to surcharged flow relies on the Preissman Slot approximation (with width 2% of the pipe's width). There is also a 2D solver for characterising overland flow but this is not used as part of this research.

There are many different rainfall runoff methods available within Infoworks ICM (kinematic wave, SCS hydrology etc.). This research uses the Wallingford Procedure (a non-linear reservoir routing method) to determine input for the urban surface drainage system. Each manhole node has a contributing sub-catchment area. A percentage runoff factor, depending on the impermeable and permeable characteristics of this sub-catchment, is used to compute the input to each manhole (i.e. a semi-lumped approach).

For the Bin Brook case study – discussed in Chapter 5 – surface drainage data came from publicly available literature and on-site observations (the study was intended as initial scoping study). In the other two case studies, local water companies (Wessex Water and Yorkshire Water) kindly provided drainage models.

The geometry and roughness data for the downstream urban watercourse were informed by river models from either the EA or a flood risk management consultant and integrated directly into the surface drainage model (the uncertainties of this are discussed in section 3.12). The rural response (from Dynamic TOPMODEL and HEC-RAS – see section 3.7) provides upstream input for the urban model. This was a loose coupling, meaning no backwater effects transferred from the drainage model up to the HEC RAS model (and the location of the boundary is carefully justified to minimise the risk of this).

3.10 Calibration

Calibration of the numerical representation of a hydrological system is necessary for any modelling methodology (Paniconi and Putti, 2015). The three different case studies each had different calibration exercises. While individual details are given in their respective chapters, this section provides a justification and description of the uniform calibration procedure used across all three.

3.10.1 Justification of Calibration Procedure

Each of the three constituent models described in sections 3.5, 3.6 and 3.9.1 was calibrated individually.

There are several reasons for calibrating Dynamic TOPMODEL and HEC RAS separately. Firstly, it makes best use of the computational efficiencies provided by each. Secondly, calibrating each separately can prevent an 'over reliance' on the lower model (i.e. HEC RAS values dominating rural response), a phenomenon which has been previously discussed (Marshall et al., 2006). Finally, it allows greater confidence when examining the individual impact of each of the two interventions (one in Dynamic TOPMODEL and the other in HEC RAS as described in section 3.8). The urban Infoworks ICM drainage models were calibrated separately as these covered different domains and come from different sources – details are provided in section 3.10.5 and in each case study.

3.10.2 Data Sources

Section 3.3.4 stressed the desirability of publicly accessible models to characterise the rural response within the modelling methodology. To complement this, the data needed to populate these models should also ideally come from widely available sources. Given the parametrically parsimonious nature of Dynamic TOPMODEL (as well as the limited requirements of a 2D HEC RAS model), most of this comes from UK national datasets. These datasets, along with how they were accessed for this research, are given in Table 3.5.

The application of Dynamic TOPMODEL and HEC RAS (described in detail across sections 3.5, 3.6 and 3.7) is reasonably uniform through the three separate case studies, but in certain instances, unique datasets have been used. These have been marked in Table 3.5.

Table 3.5 Datasets used to inform the rural modelling methodology

Type	Source	
	Spatial Data	
Terrain	• Ordnance Survey Terrain 5 DTM	Digimap[1]
	• EA lidar DTM (1m resolution) †	Digimap[1]
Land use	• Corine Land Cover 2012	CEH[2]
River Network	• OS Mastermap Water Network	Digimap[1]
Infrastructure	• OS Mastermap Topography	Digimap[1]
	Temporal Data	
Rainfall Gauge	• FOI Request	EA
	• Cambridge University Digital Technology Group †	DTG[3]
River Level Gauge	• FOI Request	EA
River Flow Gauge	• FOI Request ⋄	EA
Evapotranspiration	• CEH CHESS Explorer	CEH[4]

†refers to data used only in the Bin Brook case study (Chapter 5)
⋄ refers to data used only in Asker case study (Chapter 6)

[1] https://digimap.edina.ac.uk/
[2] (Cole et al., 2015)
[3] https://www.cl.cam.ac.uk/research/dtg/weather/
[4] https://eip.ceh.ac.uk/chess

3.10.3 Dynamic TOPMODEL

As discussed in sectiton 3.5, Dynamic TOPMODEL is discretised to create HRUs. This research has discretised catchments based on the Topographical Wetness Index (TWI) (Quinn et al., 1995). This is the ratio between the upstream contributing drainage area to a point and the topographic slope at this point. The methodology therefore assumes that areas with similar TWIs will react to rainfall in the same manner. The TWI was the primary discretisation method for TOPMODEL (Beven and Freer, 2001) and has been used as such in many studies (Ala-Aho et al., 2017; Buchanan et al., 2014; Hankin et al., 2017; Lin et al., 2006b; Metcalfe et al., 2017). The HRUs needed for coupling (discussed in section 3.7) were also incorporated, along with areas identified for tree planting (different for each case study catchment – see Chapters 4 to 7).

After defining the discretisation, the parameters which characterise the behaviour of these HRUs require calibration. As with the majority of semi-distributed (and indeed many fully distributed) conceptual models, Dynamic TOPMODEL relies on ‘effective parameters’. These assume that, despite the inevitable internal heterogeneity, the bulk behaviour of a single HRU is determined by a single parameter set (Vázquez et al., 2002). This makes determining parameter values from physical measurement difficult. Therefore, many studies, including this one, rely on the computational efficiency of a model to conduct some form of an informed Monte Carlo technique (Ballard et al., 2011; Freer et al., 2004; Kaleris and Langousis, 2017; Metcalfe et al., 2017).

In this study, a single parameter set was applied to the whole catchment (i.e. across all HRUs) – this follows methods in other Dynamic TOPMODEL studies (Liu and Gupta, 2007; Page et al., 2007; Younger et al., 2009). Although there has been general discussion on the benefits of using catchment knowledge to impose 'relative' sampling bounds of different lumped areas in a catchment (Gharari et al., 2015; Gupta and Nearing, 2014), this was deemed not pragmatic here. This is because: (1) doing so would incorporate significant complexity into the calibration procedure without definitively reducing uncertainty and (2) any lumped areas defined by land or soil type would be disrupted by the NFM and river channels incorporated into the discretisation. The bounds for each calibration are informed by the literature and a consideration of catchment characteristics (and therefore are given in each case study chapter).

The creation of parameter sets in this manner is dependent on achieving a sampling density that ensures sufficient permutations of parameter sets (Blasone et al., 2008). This research uses random sampling to create 5000 parameter sets for each case study calibration (following similar numbers in other Dynamic TOPMODEL studies (Hankin et al., 2017; Metcalfe et al., 2015, 2018)). Other techniques have been developed to allow more efficient sampling to achieve similar accuracy (e.g. Latin Hypercube (Murphy et al., 2006; Sheikholeslami and Razavi, 2017)), but given the wealth of literature following uniform sampling of TOPMODEL's effective parameters (e.g. Beven and Freer (2001); Freer and Beven (2001); Page et al. (2007)) this was deemed not necessary.

Each of the 5000 parameter sets was then run through Dynamic TOPMODEL for a specified calibration period. These calibration periods (one for each case study) will be justified separately but broadly had these characteristics: (1) sufficient duration to be comparable to other peer-reviewed work (2) reasonably recent (within last 10 years) and (3) contain a significant event on record *without* report of widespread fluvial flooding. The last of these allows focus on drainage performance being inhibited by outfall inundation, rather than out of bank flow.

Once the 5000 realisations were obtained from Dynamic TOPMODEL (using the simple channel routing mechanism described in section 3.5), they required evaluation using 'objective functions' (Pechlivanidis et al., 2011). These typically provide a numerical evaluation on the fit between the simulated and observed downstream output hydrograph. Perhaps the most commonly found objective function in hydrological modelling (and used throughout this research) is the Nash Sutcliffe Efficiency (NSE) index (Nash and Sutcliffe, 1970). A dimensionless term,E_f, it characterises the variance between the two time series (e.g. downstream hydrographs) and is calculated as shown in Equation 3.10.

$$E_f = 1 - \frac{\sum^{n}(\hat{Y}_i - Y_i)^2}{\sum(Y_i - \bar{Y})^2} \tag{3.10}$$

where n is the number of timesteps in the calibration, $\hat{Y}_i$ is the simulated value at each time step, Y_i is the corresponding observed value and $\bar{Y}$ is the mean average of the observed values.

The NSE is extensively used in the literature (Buytaert and Beven, 2009; Giudice et al., 2013; Wu and Chen, 2015), despite limitations and flaws with this metric (as discussed in section 3.12). There has also been debate over how the index should be applied and what value constitutes an 'acceptable' fit (Lin et al., 2017; McCuen et al., 2006; Schaefli and Gupta, 2007). In many cases, decisions could be considered arbitrary and based on experience (Knoben et al., 2019). For instance, Moriasi et al. (2007) reviewed use of the NSE and classified $0.75 < E_f < 1$ as '*very good*' for watershed-scale models of the hydrological system. This study uses a minimum threshold value for an acceptable simulation of $E_f > 0.8$ (similarly to many other hydrological studies (Brown et al., 2013; Pappenberger and Beven, 2004; Rossi et al., 2009)).

Moreover, the research has actually used a multi-objective function analysis by also evaluating simulations on their ability to replicate peak flow magnitude (similarly to Hankin et al. (2016)). Therefore, simulations were only deemed 'behavioural' if they were within 10% of the observed peak flow (within each calibration). This approach allows a trade-off between different characteristics of simulation realisations.

The final stage of the calibration is the treatment of the 'behavioural' simulations. One approach is the Generalised Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992, 2014), which allows for many behavioural simulations and the concept of equifinality. Equifinality allows for different model structures – and many parameter sets within a single model stucture – to produce behavioural simulations (Beven, 2006; Freer and Beven, 2001). GLUE assigns each behavioural simulation with a 'likelihood' weighting parameter which remains throughout subsequent permutations. This philosophy was adopted in the early stages of this research project, before being replaced by a deterministic approach. That change was made because the computational requirement when having many behavioural simulations from Dynamic TOPMODEL (e.g. over 200 with the objective functions detailed in this section) became prohibitive when incorporating HEC RAS when routing channel flows. The volume of simulations needed (in calibration of HEC RAS alone – see method in section 3.10.4) overwhelms the additional flexibility created by using the Controller (see section 3.6.1). Furthermore, the GLUE method remains controversial for its lack of statistical rigour (Adreassian et al., 2007; Beven, 2019; Hall et al., 2007). Hence the switch to a deterministic approach which involves choosing a single 'best' parameter set with which to characterise HRU response. While there is precedent for this (Metcalfe et al., 2017), the method inevitably incorporates uncertainty (discussed in detail in section 3.12).

This 'best' parameter set (these are given in Tables 5.1, 6.1 and 7.1 in the relevant chapters) was then carried forward to provide input for the HEC RAS model.

Table 3.6 Calibrated Dynamic TOPMODEL parameters for the three case studies

			Calibrated values (2 s.f.)		
Parameter	Units	Sample bounds	Bin Brook	Asker	Calder
$ln(T_0)$	m^2/h	4 – 10	6.1	9.3	5.1
m	m	0.001 – 0.015	0.007	0.0036	0.0064
$s_{rz,max}$	m	0.1 – 0.3	0.25	0.14	0.11
$s_{rz,0}$	%	0.98 – 1	0.98	1	1
t_d	hr/m	10 – 60	36	49	18
v_{chan}	m/hr	1000 – 2000	1100	1600	1600
v_{of}	m/hr	40 – 150	45	92	85

3.10.4 HEC RAS

The HEC RAS model used the 2D solver to route flows from distributed upstream inputs to the catchment outlet (as described to section 3.6).

The input fluxes (created using the 'best' Dynamic TOPMODEL parameter set as described in section 3.10.3) provided a constant input. The model was then calibrated by performing a sensitivity analysis of the underlying Manning's roughness value. Such a technique is common in hydraulic modelling (Bates et al., 2014, 2004; Oubennaceur et al., 2018). This research has used a single global roughness value for the whole 2D domain. The subsequent simulation hydrographs were then evaluated using the Nash Sutcliffe Efficiency, E_f, to determine which provided the best fit. The assumptions and consequent uncertainties of this approach are discussed in section 3.12.

Where pertinent in certain case studies, local culverting was representing through 'burning' the channel's path into the DTM – this technique is recognised in the literature (Getirana et al., 2009; Schwanghart et al., 2013) and is discussed in detail for each case study.

3.10.5 Infoworks ICM

Calibration of each Infoworks ICM urban drainage model was dependent on the characteristics and availability of the data obtained. Therefore, a description of each will be set out within the relevant case study.

3.11 Construction of Design Storms

This study uses idealised design storms in the evaluation of upstream NFM's impact on downstream drainage performance. This is because they offer a well-established mechanism for evaluating behaviour during extreme events (which are rarely observed) with a range of directly comparable storms between the three case studies.

The design hyetographs were derived using the Flood Estimation Handbook (FEH) method. This uses catchment descriptors, which were sourced from the CEH's Flood Estimation Handbook web service[4] and National River Flow Archives[5].

Initially, the duration of the storm (in hours) is obtained using the following equations:

$$T_p = 1.56PROPWET^{-1.09} \times DPLBAR^{0.60} \times (1 + URBEXT_{1990})^{-3.34} \times DPSBAR^{-0.28} \tag{3.11}$$

$$D = T_p \left(1 + \frac{SAAR}{1000}\right) \tag{3.12}$$

where catchment descriptors in Equation 3.11 are $PROPWET$ (indicating the proportion of time catchment soils have a moisture deficit less than $6mm$), $DPLBAR$ (the average distance to catchment outlet), $URBEXT_{1990}$ (fraction of sub-urban landcover in 1990) and $DPSBAR$ (which characterises the steepness of the catchment).

The time to peak, T_p and $SAAR$, the average annual rainfall from 1961 – 1990, are the inputs for Equation 3.12 to obtain the duration of the storm, D. Following standard procedure, this value was rounded to the nearest odd integer – meaning the Bin Brook and Todmorden case studies had design storms of 5 hours, but the larger Asker catchment saw a design storm of 7 hours.

A Depth-Duration-Frequency curve (extracted from FEH and assumed to be uniform across the whole catchment) was corrected using the areal reduction and seasonal factors to obtain the total precipitation in each catchment for each return period. This total precipitation was then distributed across the design storm profile to obtain a range of idealised storm hyetographs.

[4]https://fehweb.ceh.ac.uk/
[5]http://nrfa.ceh.ac.uk/

3.12 Uncertainties

The most commonly discussed uncertainties in hydrological modelling are typically classified as either *epistemic* or *aleatory* (McMillan et al., 2018). Aleatory uncertainties arise from inherent natural variability within the system, but can be treated using statistical theory (Refsgaard et al., 2007). Conversely, epistemic uncertainties arise from lack of knowledge about the system ('known unknowns') and are not well described by statistical theory. Increasingly, there is discussion between hydrologists about whether the distinction between the two is helpful, with Nearing et al. (2016) arguing that at a 'micro' scale, all aleatory measurement error results from physical inconsistencies.

Any numerical representation of a hydrological system, including the constituent models justified in this chapter, contains assumptions which create aleatory and epistemic uncertainty. The purpose of this section is to identify, emphasize and evaluate the impact of this uncertainty within the methodology. A later section (section 9.6.2) discusses the role of uncertainty in interpreting the results.

3.12.1 Sources of Uncertainty

Refsgaard and Storm (1996) identifies four key categories from which these two types of uncertainty arise (which are mirrored for hydraulic channel modelling in Butts et al. (2004)):

1. Error in input data, $[\mathbf{D_{inp}}]$. Initial and boundary conditions (in time and space dimensions) have associated random or systematic error.

2. Error in recorded data, $[\mathbf{D_{rec}}]$. This is random or systematic error in the data used to calibrate and validate the model output.

3. Error in model structure, $[\mathbf{S}]$. Different model structures are essentially different numerical approximations of the hydrological system and therefore each has intrinsic error.

4. Error in parametrisation, $[\mathbf{P}]$. Parameters are used to characterise a hydrological response and so any error is dependent on the underlying model structure. For example, the error of parameters within a fully-distributed, physically based model (discussed in Madsen (2003)) will be treated differently to those in a semi-distributed, semi-conceptual model (discussed in Beven and Freer (2001)).

This classification of different sources of uncertainty will now be used to assess assumptions made (and consequent error incorporated) within the coupled methodology.

3.12.1.1 Model Construction

Dynamic TOPMODEL

Freer et al. (2004) states that hydrological models use "highly simplified mathematical constructs that cannot represent all the details of the many interacting processes within a natural system." As a result, the inherent assumptions made within each of the constituent models within the selected coupled methodology will incorporate different forms of error [**S**].

Freer et al. (2004) evaluates the plausibility of Dynamic TOPMODEL's semi-conceptual, semi-distributed structure and highlights the lack of explicit consideration of mechanisms such as preferential macropore flow paths or variability in porosity at different soil horizons.

The semi-distributed structure of the model is also dependent on the spatial discretisation strategy. This research primarily uses the theoretical wetness index (TWI) to identify hydrological similar areas (this is a long established method, as discussed in section 3.10.3). This method necessarily introduces a subjective influence in how the catchment responds to rainfall [**P**]. This rainfall is applied using Thiessen polygons, which results in spatial extrapolation of gauged rainfall [$\mathbf{D_{inp}}$], which may itself be flawed [$\mathbf{D_{rec}}$]. This potential error is mirrored in the evapotranspiration data, which is extrapolated from a single point from the CHESS database (with no consideration of underlying topography or land use) [$\mathbf{D_{inp}}$][$\mathbf{D_{rec}}$].

HEC-RAS

The hydraulic model component, HEC-RAS, uses the diffusive wave equation (justified in section 3.10.4) which, by being an approximation of the physically-based shallow flow equations, potentially introduces another source of error [**S**].

This solver is used to characterise flows under gravity and friction forces, with the topography informed by a 1m DEM in the Bin Brook case study and a 5m DTM for the Asker and Todmorden studies. This was necessitated by the available data. However, Savage et al. (2016) highlights the influence of DTM resolution on the output (and computational requirement) from catchment-scale hydraulic models. It could be argued that both resolutions may not appropriately capture channel morphology (although for the 5m resolution clearly this is more questionable) [$\mathbf{D_{inp}}$]. This could alter flow lengths and concentration times, although there is precedent for using 5m resolution data (Fonseca et al., 2018; Jahandideh-Tehrani et al., 2020). There is also potential for error in the recording of the LiDAR data (Entwistle and Heritage, 2017) [$\mathbf{D_{rec}}$].

Rural Coupling

The coupling has been achieved using a 20*m* buffer being burnt into the Dynamic TOPMODEL discretisation and the same 'footprint' being used as the input boundary for the hydraulic model (this is justified in section 3.7). This significantly simplifies the complex spill mechanisms from the field zone into the channel zone. However, this coupling also results in at least three other possible sources of uncertainty. Firstly, there is no distinction between surface and sub-surface contribution to the channel reaches which, in the small case study catchments, are not 20*m* wide [**S**] [$\mathbf{D_{inp}}$]. Secondly, this input is averaged along the entire reach, which neglects local anomalies [**P**]. Thirdly, the loose-coupling means there is no feedback between the two models and no consideration of how levels in the channel may influence spill from the riparian zone [**S**].

Infoworks ICM

The drainage components of the Infoworks models for Bridport and Todmorden (detailed in Chapters 6 and 7) were respectively developed by Wessex Water and Yorkshire Water. The equivalent for the Bin Brook was informed by asset maps from Anglian Water. There is therefore significant potential for geometric error in this data [$\mathbf{D_{inp}}$].

Furthermore, to achieve the integrated urban environment, external river models have been incorporated into the Infoworks ICM model. These come from a Halcrow river study (Bin Brook) and the EA (the Asker and Calder). The data collection procedures are therefore unclear [$\mathbf{D_{inp}}$]. The 1D models are also dependent on the resolution of section data [$\mathbf{D_{inp}}$].

The amalgamation of the two models within Infoworks ICM introduces a key potential source of error because the local geometry around outfalls is critical in determining their behaviour under severe events. The river section data (from the river model) and outfall height data (from the drainage model) have been collected separately. Moreover, the river section at each outfall had to be extrapolated from surveyed sections upstream and downstream. Although the physical geometry was visually inspected to ensure correlation with the numerical representation in Infoworks, no additional river surveying was undertaken. As the results are highly dependent on local geometry around outfalls. This is a significant source of uncertainty [$\mathbf{D_{inp}}$].

Urban Coupling

The coupling between rural and urban models occurs with the output from HEC-RAS providing input to Infoworks ICM. Once again this is a loose couple, meaning there is no feedback between the two models. As a result, there is no capturing of any backwater effect which may result from constriction in the urban channel from bridges or culverts. This risk can be largely mitigated with careful selection of the boundary (at a smooth gradient, well away from channel infrastructure), but the potential for error remains [**S**] [$\mathbf{D_{inp}}$].

3.12.1.2 Model Calibration

Dynamic TOPMODEL and HEC-RAS

The two rural models were calibrated using downstream river gauge data, making the existence of gauges a requirement in the selection case studies. In two cases – the Bin Brook and Calder – the EA gauges measured level data only (as their primary function is to inform flood warning systems). There were insufficient spot flow records to create a depth-discharge relationship, necessitating the construction of a rating curve. This was done with the Manning's equation:

$$v = \frac{R^{2/3} \times s_0}{n} \tag{3.13}$$

where v is cross-sectional average velocity, R is the hydraulic radius, s_0 is the slope of the hydraulic grade line and n is the Manning coefficient. The R, s_0 (which, by assuming constant water depth, was taken as equating bed slope) and n values were informed by the river models (discussed above in section 3.12.1.1).

The two constructed curves are given in Appendix B. There has been considerable recognition of the uncertainty incorporated in modelling when using rating curves (Coxon et al., 2015; Domeneghetti et al., 2012). Primarily, error can come from alteration of the gauging section (resulting from sedimentation, erosion, plant growth etc.) (Tomkins, 2014) or extrapolation of rating curve beyond observed domain (Kuczera, 1996). Although the gauging sections in both catchments were visually inspected, the assumptions used in the construction of the rating curve (as well as the dependency of the calibration) means this is a significant potential source of error [$\mathbf{D_{rec}}$].

This uncertainty has been evaluated in the past using a variety of techniques, including statistical regression approaches on rating curves (Petersen-Øverleir and Reitan, 2005) and Bayesian approaches (which allows incorporation of knowledge using prior distributions – see Appendix C) (Juston et al., 2014).

The Monte Carlo calibration procedure for Dynamic TOPMODEL incorporated various other forms of error through subjective modelling decisions (although these are justified by previous literature in section 3.10.3). These include (i) the sampling ranges [$\mathbf{D_{inp}}$] (ii) evaluating simulations solely on ability to replicate peak flow magnitudes across the calibration period and (iii) using a single parameter set to characterise catchment response [**P**][$\mathbf{D_{inp}}$].

Another key component of the calibration procedure is a reliance on the Nash-Sutcliffe Efficiency metric, whose implicit biases have been questioned in the literature. One of the principal issues with the NSE is the squared differences between simulated and observed values. This means that errors are magnified at peak. As a result, higher NSEs are biased towards model performance during peaks and less so during base periods (Krause et al., 2005; Legates and McCabe, 1999). Bergström (1991) also point out that the NSE is site specific and dependent on the quality of observed data. McCuen et al. (2006), amongst others, highlight a time-offset bias which is particularly seen when a rainfall gauge is not located within a watershed (or when spatially distributed rainfall is not accounted for).

Infoworks ICM

The calibration of the urban model relied on sparsely available data. As a result, each case study used a slightly different technique and this is discussed within each relevant chapter (see sections 5.3.1, 6.3.1 and 7.3.1).

3.12.1.3 Representation of NFM

Section 3.8 gives a description and justifies how tree planting and large woody debris is represented within the coupled model structure. Deterministic representation of such interventions is highly uncertain because of the nascent evidence base (discussed in section 2.2) [$\mathbf{D_{inp}}$]. Furthermore, the research has relied on values pertaining to studies in other catchments with different in-situ conditions, creating more uncertainty [$\mathbf{D_{inp}}$]. These values have also been applied uniformly across different intervention locations across the catchment [**P**].

A sensitivity analysis of the shifts used to represent tree planting is given in section 9.6.2 when evaluating the uncertainty of intervention representation on the trends identified in the results. However, taken together, the parameter shifts achieve a modest downstream attenuation (see the later results chapters) that is in line with findings from other studies that evaluate the impacts of catchment-scale tree planting (Dixon et al., 2016; Iacob et al., 2017). The intervention is perhaps conservative as it does not account for interception or canopy redistribution caused by the tree planting intervention (Gutmann, 2020; Muzylo et al., 2009). Doing so could magnify impact of tree planting on catchment response and thereby have a greater moderating effect on downstream water levels.

3.12.2 Treatment of Uncertainty

Section 3.12.1 identifies and evaluates different sources of uncertainty within the coupled modelling methodology.

Various frameworks exist to aid the quantification of uncertainty behind model structure, parameter and calibration techniques. Their purpose is to offer a 'degree of certainty' around an absolute conclusion. Techniques to do this include sequential uncertainty fitting (Kumar et al., 2017b; Narsimlu et al., 2015), particle swarm optimisation (Chen et al., 2016), the generalised likelihood uncertainty estimation (Beven and Binley, 2014; Mirzaei et al., 2015) and Bayesian techniques (Liu et al., 2017; Mara et al., 2016). Arguably, the last two are the best-known. Both are typically based on Monte Carlo techniques and descriptions of each are given in Appendix C. The primary benefit of Bayesian approaches is the ability to incorporate existing knowledge of parameters using statistical distributions (Jeremiah et al., 2011). GLUE approaches are also built on parameter distributions (either uniform or informed by observation) but allow for the principle of 'equifinality' where more than one parameter set can be defined as behavioural and carried forward in the analysis. By doing so, it is argued that GLUE techniques amalgamate consideration of both parameter and model structure uncertainty (Freer and Beven, 2001). Nonetheless, the subjectivity (and perceived lack of statistical vigour) in determining the behavioural threshold, as well as the likelihood function used to rank acceptable parameter sets has been somewhat controversial (Jin et al., 2010; Stedinger et al., 2008).

Hankin et al. (2017) detail an interesting approach to incorporating uncertainty within an analysis of NFM with Dynamic TOPMODEL catchment model. They used a two dimensional approach – a GLUE analysis to determine multiple behavioural simulations and then applied a 'fuzzy' approach (i.e. a range of parameter changes justified by the literature) for NFM replication on each acceptible parameter set. This allows confidence intervals to be placed on intervention impact downstream.

Initially, the intention for this research was to follow a similar GLUE-based approach to that of Hankin et al. (2017) (given the very limited parameter data with which to inform the statistical distributions for a Bayesian approach). However, as well as the doubts about the possible lack of statistical vigour in GLUE referred to above, two further important reasons also inhibited the application of a GLUE analysis for this particular study. Firstly, the computational requirement of HEC-RAS (very approximately 50 times that of Dynamic TOPMODEL) means that the scope of the modelling exercise would be severely limited, if not prohibitive. Secondly, the metric under consideration in Hankin et al. (2017) was downstream attenuation of catchment response (i.e. peak reduction). However for this research, which nuances the evaluation of NFM impact (i.e. incorporating the influence on drainage performance), such an approach is not pragmatic. The behaviour of each outfall would be evaluated using multiple behavioural simulations (in the case of Hankin et al. (2017) there were approximately 350 of these) and this would be required for each of the multiple number of upstream NFM scenarios set out in Chapters 5 to 7. Again, this would entail prohibitively large computational requirements (a similar argument is noted – for a different objective – within McMillan and Brasington (2008)).

As a result, this study made a pragmatic methodological decision to use a deterministic approach in model calibration and NFM representation. This necessitates cautious interpretation of absolute results. However, the use of three separate case studies is sufficient to allow the identification of broader trends both within and across catchments. Section 9.6.2 discusses how the trends in the results could be influenced by the sources of uncertainty identified in section 3.12.1

3.13 Summary

This chapter began by reviewing literature on catchment-scale modelling approaches in order to justify the chosen methodology, which consists of Dynamic TOPMODEL, HEC-RAS and Infoworks ICM (see Figure 3.1). It then gives a detailed explanation of the solvers behind each of these models.

The representation of NFM interventions within this research, along with the calibration procedures used in each of the subsequent case studies are also discussed. The chapter finishes with a discussion of the intrinsic uncertainties within the methodology.

The first three chapters of this thesis have laid the foundation for applying a coupled modelling methodology to three separate case study catchments in order to evaluate the central research question.

Chapter 4

Case Study Selection

Having justified and described the modelling methodology used throughout this research, the thesis will now turn to presenting results from three discrete catchment studies. They are presented separately in Chapters 5, 6 and 7. The locations of these case studies are given in Figure 4.1. This chapter offers a brief justification for their selection.

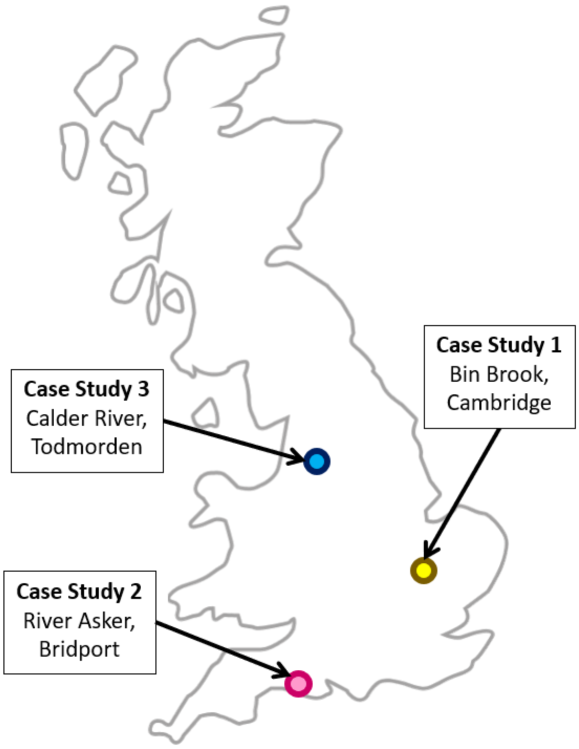


Figure 4.1 Locations of the three case study catchments used in this research project

Each case study contains a predominantly rural area contributing to a downstream urban watercourse which has an adjacent residential area with acknowledged surface water flood risk resulting from poorly performing drainage. However, beyond this, the catchment characteristics of each vary significantly. The diversification created by the multiple case study approach allows greater interrogation of the central research question.

All three locations are based in the England. This is a methodological choice, justified by the need to retain sufficiently tight scope when evaluating existing knowledge for both NFM and surface water management policies and practices. It also means the catchments have comparable vegetation and temperate climate conditions. There could be further applications of the conclusions reached in other countries with different climates, environments, drainage systems and flood management policies. This will be recommended as an area for further work.

The first study conducted was the Bin Brook catchment on the outskirts of Cambridge (Chapter 5). In a downstream area of this catchment there is a locally acknowledged and well-recorded problem with surface drainage within a contributing housing estate (and an interest in mitigating fluvial risk through upstream NFM interventions). This case study was initially used to trial the modelling methodology across the various domains. This was helped by the fact the location was easily accessible and local contacts could be used to help data population. This study proved successful (both in trialling the model and generating informative results) and so evolved during the research project into a full case study.

The second study (Chapter 6) focuses on a rural area of Dorset and the downstream town of Bridport, where the local water company acknowledges the problem of outfalls being blocked by elevated river levels. The catchment is significantly larger and offers a much more varied topography and hydrogeology than the Bin Brook.

The final case study covers a sub-catchment of the upper Calderdale and the downstream town of Todmorden. This area was chosen in conjunction with Yorkshire Water, who have repeatedly identified submerged outfalls as exacerbating local flood risk. The rural catchment is steep sided (differing from the first two case studies) and there is significant interest from the LLFA in implementing upstream NFM in mitigating fluvial flood risk. This is intended as the lead case study, with results presented in both Chapters 7 and 8.

Chapter 9 compares and contrasts the results across all three case studies. By scrutinising the results from across three case studies, the research is able to offer more robust discussion on the ability of upstream NFM to influence downstream drainage performance rather than answering an isolated design question for a single catchment.

Chapter 5

Bin Brook Case Study

5.1 Introduction

This chapter applies the methodology described and justified in Chapter 3 to the first case study – the Bin Brook catchment. The chapter is self-contained, in that it details the catchment model and the subsequent modelled NFM intervention before discussing the results. The following Chapters 6 and 7 are constructed in a similar manner (the ethos behind this approach is discussed in Chapter 4). The results for this chapter have been reported in Ferguson and Fenner (2020d).

5.2 Location

The Bin Brook catchment is part of the Cam and Ely Ouse river basin in Cambridgeshire (see Figure 5.1(a)). The brook rises in the village of Hardwick at 60-65m above Ordnance Datum (AOD). It passes the southern edge of the village of Coton before crossing the Coton Countryside Reserve. It then flows underneath the M11 motorway before it turns to follow the Barton Road, passing the Laundry Farm (a university holding). The river has been gauged at this point since 2008 (a level gauge – approximately 10m AOD). Just downstream of this, the channel is a designated 'main river'. Main rivers are those where the EA "*carries out maintenance, improvements or construction work [..] to manage flood risk,*" (DEFRA, 2017). Other, 'ordinary watercourses' are under the jurisdiction of LLFAs and IDBs.

The channel flows alongside the Barton Road for $\sim 500m$ before turning northwards to the Gough Way Culvert. The culvert has a 1500mm diameter and transfers flows for $\sim 150m$ underneath the Gough Way housing estate (South Cambridgeshire District Council and Cambridge City Council, 2010). The Gough Way housing estate on the fringes of Cambridge (containing approximately 130 properties) is the urban environment focus for this case study (see Figure 5.1(b)). At the entrance of the culvert a flood relief channel, built in the early 1980s to help protect the housing estate, runs parallel with Bin Brook and flows around the western and northern edges of that development. It rejoins the Bin Brook beyond the lower end of the culvert. From there, the channel flows northeast before crossing Queens Road and Grange Road and then feeds into diverse streams and channels in the Backs and in various College gardens before it eventually reaches the Cam at Jesus Green.

The catchment above the river gauge (shown in Figure 5.1) is approximately $11km^2$ – about 80% of this area is intensively farmed rural land. The geology varies across the catchment. The uplands are dominated by superficial deposits of clay and chalk glacier till. An exposed layer of chalk runs through the centre of the catchment. This is entirely underlain by a thick Gault clay which becomes exposed across much of the lowlands. The soils are deep ($> 1m$ depth) but of low permeability, meaning the catchment response is typically flashy and dominated by shallow soil behaviour. Despite being a low-lying catchment in a dry area of the country (average annual rainfall between 2012 and 2017 was 590mm), this creates a fluvial flood risk downstream for the Gough Way housing estate.

5.2.1 Flood History

The fluvial flood risk is exacerbated by a culvert which transfers flows underneath the estate (see Figure 5.1). Despite the existence of a bypass channel, the under-sized culvert creates a throttling effect for flows seen in a greater than a 1 in 5 year event (Environment Agency, 2003b).

There have been two recorded major fluvial flood events with damage to properties in the Gough Way Estate. The first was in May 1978 – details of the impact are limited but the event did provide the catalyst for the construction of the aforementioned flood relief channel.

An October 2001 event caused flooding to at least 28 homes with a depth up to 0.9m (Environment Agency, 2003a). At the time, it was estimated widespread property flooding would occur during a 1 in 25 year event (Environment Agency, 2007).

This event prompted the establishment of a community group which lobbied local and national government for a fluvial flood risk mitigation scheme. The lobbying from this group resulted in a study conducted by Halcrow (now Jacobs Engineering) which evaluated four options (do nothing, maintain the existing level of risk, increase capacity of flood relief channel or create a $150,000m^3$ storage pond just upstream of the M11). The last option was popular with the local landowner (the Cambridge Preservation Society – now Cambridge Past, Present and Future) and the £2.5 million project underwent further appraisal by the EA in 2007 (Environment Agency, 2007) but was eventually rejected. This was partly the result

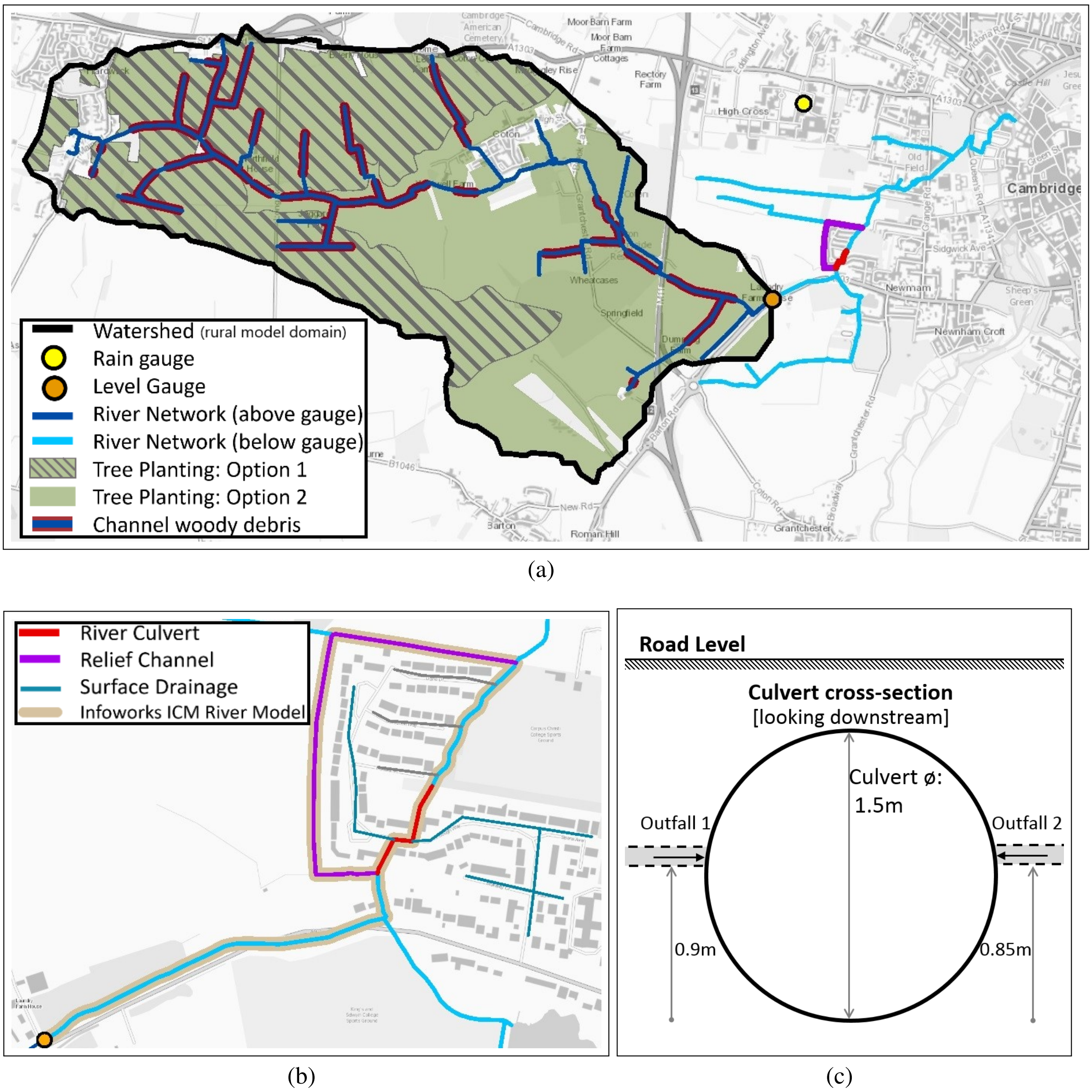


Figure 5.1 (a) The Bin Brook catchment and location of upstream NFM interventions (b) the Gough Way culvert and the contributing surface drainage and (c) cross section of the culvert

of (i) financial objections and (ii) Cambridge Water objecting to the intervention overlaying their pipes).

Since this time there has been basic property-level protection installed on the most high risk properties (K. Glover 2018, *pers. comm.*). The annual 'Gough Way flood mitigation meeting' (attended by the author in 2018 and 2020) continues to provide a contact point between residents, the EA and the Cambridgeshire County Council (the LLFA) and other local authorities. The EA has an annual contract to clear the flood relief channel of vegetation and maintains a flood warning system consisting of the upstream level gauge, camera readings at the culvert entrance and regular cleaning of the trash screen at the culvert entrance – see Figure 5.2.

(a) (b)

Figure 5.2 Gough Way culvert entrance with (a) base flow and (b) calibration event on July 12th 2012 (courtesy of Keith Glover)

There is also risk of surface flooding. In the 2014 update to the local SWMP, the Gough Way estate is highlighted as a 'wet spot' and ranked the Bin Brook as the 9th highest priority score across the Cambridgeshire county (out of 279 locations) (Cambridgeshire County Council, 2014).

The majority of surface drainage for the housing estate drains directly into the underground culvert (see Figure 5.1(b) and (c)). Local residents anecdotally reported several instances of surcharging and nuisance flooding on the Gough Way estate over the last decade (K. Glover, T. Rochford, 2018 *pers. comm.*). These instances primarily refer to large areas of standing water on the estate's road (it was speculated that they could result from poor drainage) but at no point was this sufficient to cause property flooding.

5.2.2 Available Data

The data sources common to all three case studies have been given and justified in section 3.10.2 and Table 3.5. This section provides more detail relating specifically to the Bin Brook case study.

The underlying DTM came from EA lidar data with a spatial resolution of 1m. This data was used to delineate a catchment watershed using the SAGA GIS toolbox (open source script through the freely available QGIS program). The river network (shown in Figure 5.1(b)) was obtained from the OS MasterMap Water Network. Evapotranspiration data was obtained from the CEH CHESS Explorer.

Rainfall data was extracted from the (freely accessible) database for the Cambridge University Digital Technology Group weather station. The rain gauge (shown in Figure 5.1(a)) is located $\sim 1km$ outside of the watershed in west Cambridge, but is at a similar elevation. This data was obtained in total mm fall across each 30 minute time interval with an existing record going back to 2003. This was re-sampled to a 15 minute interval to match the flow data.

The river gauge (discussed above and shown in Figure 5.1(a)) records water levels at a 15 minute interval (record available from 2008 through an FOI request to the EA). It is located approximately 500m upstream of the housing estate. The primary purpose of the gauge is to feed into the EA's flood warning system for the downstream estate and unfortunately there is insufficient spot flow data to construct a rating curve. Therefore, the existing spot flow records (also obtained from the EA) were used to provide confidence in a rating curve constructed using surveyed cross-sectional, bed slope and roughness data (from a previous unpublished hydraulic study conducted by Halcrow in 2007) providing the inputs for the Manning's Equation. The details of this constructed rating curve are given in Appendix X.

5.3 Model Construction

5.3.1 Calibration

As discussed in section 3.7, Dynamic TOPMODEL and HEC RAS were coupled by 'burning' HRUs into the hydrological model's discretisation around each of the 28 river reaches. The coupled model was constructed to produce a catchment flow output at the downstream river gauge. This then became the input for the urban Infoworks ICM model. The intervening river reach, as well as the surface drainage network in the estate, was incorporated into one integrated Infoworks ICM model. The urban watercourses incorporated into the drainage model (which include the flood relief channel) are highlighted in Figure 5.1(b). Both the urban watercourses and surface drainage around the Gough Way estate are modelled as 1D domains.

Geometric (and roughness data) for both the river reaches and flood relief channel were obtained from the Halcrow's 2007 hydraulic study. Geometric (and geographic) data for the estate's surface drainage came from an Anglian Water asset map (Cox, 2013). Unfortunately, there was no flow data with which to validate this urban drainage model. So, after the rural calibration (see the following section), behaviour of the ICM model was compared with anecdotal evidence from local residents who witnessed the calibration event. The model's replication of river levels directly upstream of the culvert matched resident testimony – the backwater effect meant both the river and flood relief channels were full, but no fluvial flooding of the estate occurred. Residents did not report surface flooding during the event but did state there was significant ponding of water on the estate's main road from manholes closest to the river culvert. This behaviour was replicated in the drainage model, with a total surface water volume of $23.7m^3$ (see Table 5.2). In the absence of any other available data, the model was deemed suitable for approximating the behaviour of the estate's surface drainage.

The available data was used to calibrate the coupled modelling methodology for a summer storm experienced in 2012 (estimated as a 1 in 15 yr. storm). This storm was preferred because (1) it is the largest event experienced in the last decade; (2) it did not cause significant fluvial flooding (such events are not the focus here) and (3) there is anecdotal evidence from local residents that during the event there was nuisance flooding resulting from poor performance of the surface drainage system.

Table 5.1 Calibrated Dynamic TOPMODEL parameters for the Bin Brook

Parameter	Units	Value (2 s.f)
$ln(T_0)$	m^2/h	6.1
m	m	0.007
$s_{rz,max}$	m	0.25
$s_{rz,0}$	$\%$	0.98
t_d	hr/m	36
v_{chan}	m/hr	1100
v_{of}	m/hr	45

The model was run with a 15-minute time step from 00:15 on 1st July 2012 until 00.00 on the 4th September 2012. This calibration length (65 days) is comparable with other, similar studies (Metcalfe et al., 2017, 2018). Calibration of Dynamic TOPMODEL was achieved using a Monte Carlo approach, which consisted of 5000 parameter sets (randomly

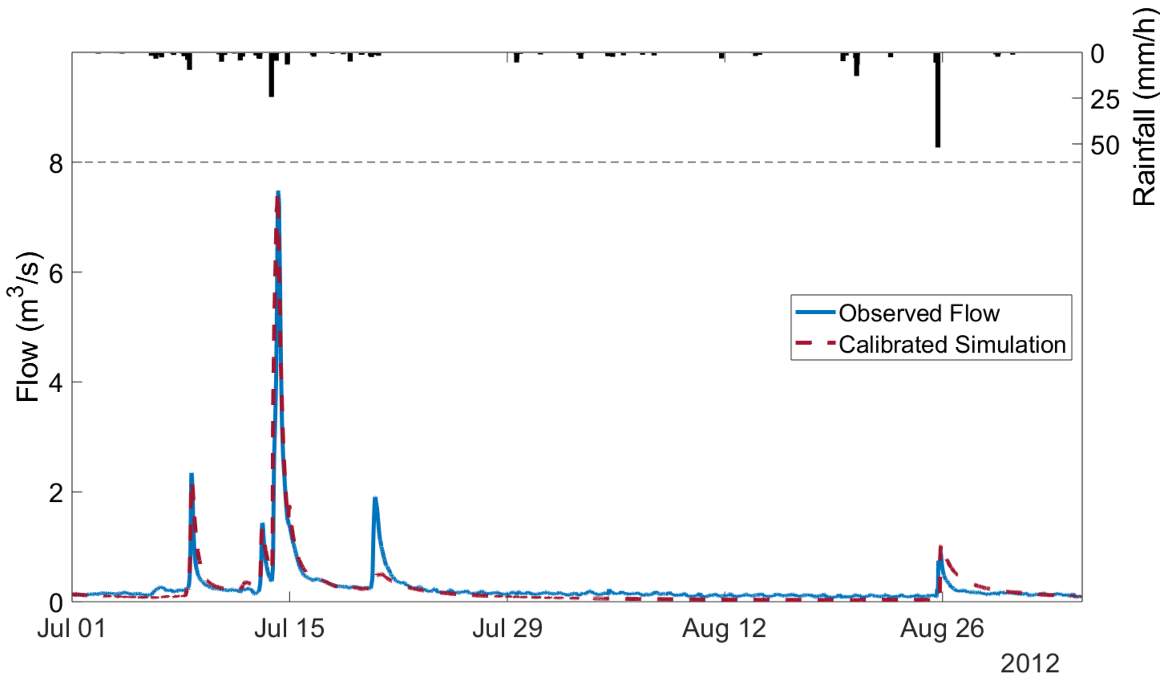


Figure 5.3 Comparison of Observed and Simulated Flow at Bin Brook river gauge

sampled between the ranges given in Table 3.6). As discussed in section 3.10.3, a single ‘best’ Dynamic TOPMODEL parameter set was used (given in Table 5.1). The subsequent sensitivity analysis used to calibrate the HEC-RAS model (section 3.10.4) gave a final global hydraulic roughness value of $n = 0.023$ (i.e. applied uniformly to all channel reaches). The simulated and observed flows are compared in Figure 5.3.

The numerical simulation produces a reasonable approximation (see section 3.10.3 for discussion) of the observed flow, with the Nash Sutcliffe Efficiency (NSE) (Equation 3.10) being 0.83. The simulated response is slightly flashier with the peak arriving at 05:30 on the 14th July, 45 minutes (three time steps) before the observed. The simulated peak magnitude very closely matches that observed (within 2%), although this would be expected given the method of calibration. The timing and magnitudes of three of the smaller peaks are also reasonably replicated, although the flashiness of the final peak is not captured. It is hypothesised this might result from the model’s evapotranspiration (which was informed by CEH’s daily maximum potential data) leading to drier soil conditions than those seen in reality. This might also explain the under-predicted base flow, although it is also known that during the summer an upstream waste water treatment plant contributes to flows. However, the biggest discrepancy in the calibration simulation is the fact it does not reflect the magnitude of the event on 20th July. One possible explanation is that the rainfall gauge, being 1km outside the watershed (see Figure 5.1(a)), has not experienced the rainfall event experienced by the catchment. Despite this, the calibration was deemed adequate to provide a basis with which to evaluate how NFM interventions might affect the performance of surface drainage in the downstream estate.

5.3.2 NFM Intervention

Following calibration of the catchment model, the NFM interventions were incorporated into the model.

There has been sustained local interest in implementing NFM within the case study catchment to improve water quality and reduce the flashy response experienced by the estate (Environment Agency, 2003a). The Cam & Ely Ouse (CamEO) Catchment Partnership (a CMP) has explicitly identified the Bin Brook as a target for NFM and habitat improvement (Cam and Ely Ouse Catchment Partnership, 2018).

As discussed in section 3.8, two forms of hypothetical intervention were evaluated: (1) in-channel large woody debris and (2) catchment-scale afforestation. Their hypothesised extents are shown in Figure 5.1(a).

The afforestation hypothesised two potential extents. The first (‘Option 1’) modelled trees across all of the EA’s WwNP opportunity mapping for catchment woodland (essentially areas of uplands glacial till). This amounts to 45% of the total catchment area. The second conjectured tree planting extent (‘Option 2’) was across all arable land in the catchment (approximately 79% of the total area). While physical replication of this would be extremely ambitious, there is also a degree of precedent. A nearby Cambridgeshire farm has created the largest agro-forestry project in the UK and has planted over 125 acres with apple trees and wildflowers (Burgess, 2017; Newman et al., 2017).

As discussed in section 3.3.2, the modelled in-channel woody debris was applied in reaches crossing arable land that are at least 50m from any infrastructure (e.g. bridges, buildings or culverts etc.).

5.4 Results

The calibrated model was used first to produce downstream hydrographs for (i) the July 2012 event and (ii) a series of design storms (of 5, 10, 20, 30, 50 and 100 year return periods). For each of these events, four different NFM intervention scenarios were then replicated in the coupled model. These four scenarios were: (1) large woody debris only (2) tree planting option 1 only (3) tree planting option 2 only and (4) an 'NFM-max scenario'. This 'NFM-max' consists of both large woody debris and tree planting option 2 being applied together in the upstream catchment.

5.4.1 Impact on Flow

Figure 5.4 illustrates how each of these four scenarios attenuates the rural response during the 2012 peak event and five different design events (the 5, 10, 20, 50 and 100 year storms).

Figure 5.4 shows that the greater the intervention, the more attenuation there is of the catchment's modelled response. The max-NFM scenario (where catchment-wide tree planting and woody debris are both implemented) is consistently the most effective at reducing and delaying the response. As the severity of the design storm increases, attenuation from upstream interventions diminishes. Despite this, the downstream peak response from a 100 year storm can still be reduced by up to 22.8%.

The figure shows that the calibration peak (approximately a 15 year event) is reduced by 7.6% with tree planting option 1 (i.e. 45% afforestation) and 14.4% with option 2 (79% afforestation). However, neither option has any impact on the timing of this peak. This contrasts with the greater impact tree planting has on the design storms (for option 2, the 20 year event can be reduced by 28.5% and delayed by 30 minutes). This inconsistency could result from differing hyetograph shapes. During the calibration peak event, approximately one quarter of the total rainfall (12.2mm) fell during the first half hour. This compares with the 1.2mm (approximately 3%) falling in the same time during the 20 year event. It is hypothesised that the initial pulse of rainfall during the calibration event largely overwhelmed the effect from the small increase in shallow soil permeability created in Dynamic TOPMODEL. This highlights how NFM interventions might respond differently to varying rainfall patterns.

It is also worth noting how the two interventions appear to be have slightly different influences on the modelled downstream hydrograph. The tree planting intervention creates modest reductions in peak magnitude, but has a minor influence on delay. Conversely, the in-channel debris causes smaller reductions in peak magnitudes (up to 3.1%), but is more effective in postponing peak arrival (by up to 90 minutes in a 5 year event). This could be a result of the catchment's shallow topography. In Dynamic TOPMODEL, the

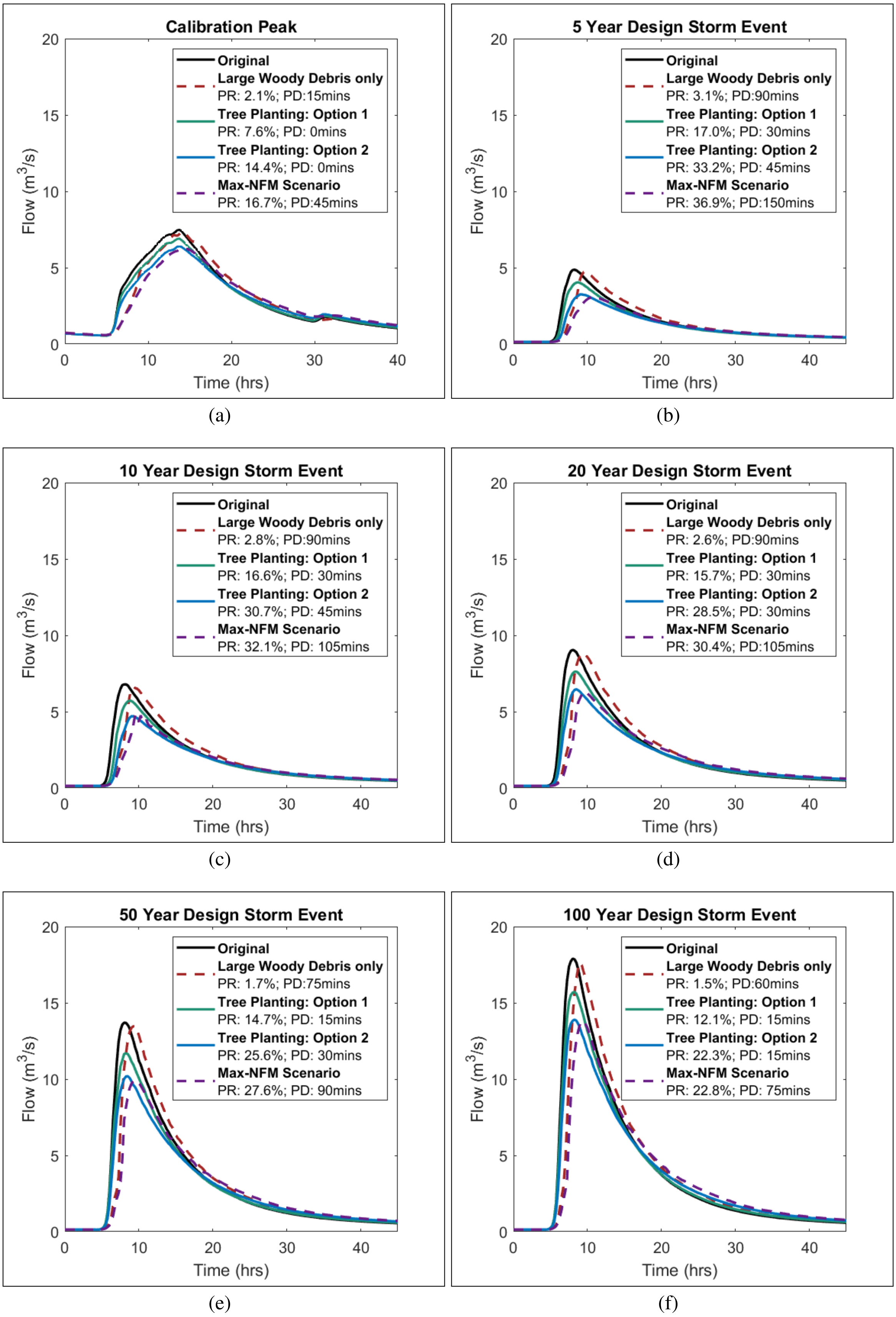


Figure 5.4 Impact of four different NFM intervention scenarios on peak reduction (PR) and peak delay (PD) during the July 2012 calibration and five design storm hydrographs

greater sub-surface flux created by tree planting creates storage but has less influence on slowing the time to peak. On the other hand, by representing large woody debris as an increase in roughness in HEC-RAS, the coupled model is not appropriately capturing the routing storage effect created by the throttling (and consequent backwater effect) induced by a series of individual woody dams. This could explain the resultant hydrograph being delayed without significant reduction in peak magnitudes. The divergence in downstream impact could indicate that specific interventions might be used to achieve a desired form of downstream impact. Investigating this would require alternative modelling structures and NFM representations. Overall however, the NFM-max scenario (consisting of both forms of intervention) amalgamates the two effects and has the greatest impact on both peak magnitudes and timings.

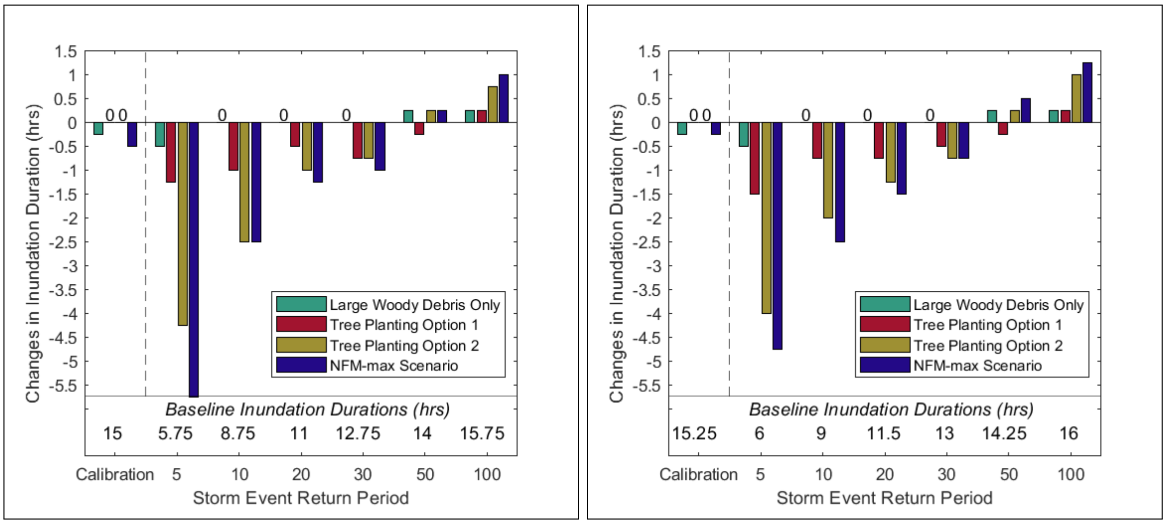
5.4.2 Impact on Outfall Inundation

While attenuation of downstream flows has traditionally been the focus of many NFM studies, this research is primarily concerned with the consequent effects on water levels in downstream reaches and how these levels influence the ability of the two surface drainage outfalls to discharge directly into the culvert. The location and local geometry of these two outfalls are shown in Figures 5.1(a) and 5.1(b). The Infoworks ICM model was used to establish the time that water levels were high enough to drown the two outfalls (see Figure 2.5 for exemplar).

Figure 5.5 shows the baseline inundation durations (i.e. those caused by the storm through the calibrated, unaltered catchment model) and the subsequent changes created by the four different NFM scenarios. The baseline and subsequent NFM effects are slightly different for each outfall because of the small difference in invert heights (see Figure 5.1(c)).

There are several trends visible in Figure 5.5. The greater the flow attenuation achieved by an intervention scenario, the greater the change in downstream outfall inundation. Alongside this, the biggest reductions in outfall inundation occur during more frequent events. During the 5 year event, the 5.75 hours of inundation at Outfall 1 is completely removed by the max-NFM scenario. The same intervention, however, is not enough to prevent flows continuing to briefly submerge Outfall 2 (which is lower). As the severity of the design storms increase, the baseline inundation duration increases. At the same time, the influence of upstream interventions diminishes. Therefore, for a 30 year event, Outfall 2 is inundated for 13 hours but the max-NFM scenario only creates a reduction of 1 hour.

It also worth noting that the calibration peak, approximately a 15 year event, causes at least 15 hours of inundation – more than the 50 year storm. This highlights how different forms of rainfall event can maintain elevated water levels in a downstream watercourse



(a) (b)

Figure 5.5 Inundation Periods of the two outfalls ((a) Outfall 1 and (b) Outfall 2) discharging from Gough Way estate into underlying culvert

(thereby submerging outfalls). The limited attenuation of this event is one reason for the very modest reduction in inundation durations (up to 0.5 hours under the max-NFM case). The second is the throttling effect of the under-sized culvert. The resultant backwater effect means that flows inside the culvert are maintained for longer than they otherwise would be. This will reduce the resultant impact from NFM interventions.

Figure 5.5 also demonstrates that upstream NFM interventions can also have a detrimental impact on inundation duration of outfalls. While the effect of upstream interventions has significantly diminished by the 100 year event (see Figure 5.4(f)), there is sufficient attenuation (from the tree planting option 2 and max-NFM scenarios) to prolong the time outfalls are submerged by 0.5 hours. Interestingly, this means the interventions that are most effective in reducing inundation periods during frequent storms are the most susceptible to having an adverse effect in severe events.

5.4.3 Impact on drainage performance

The changes in outfall inundation within the culvert have consequences for the behaviour of the contributing surface drainage systems. These have been evaluated using the Infoworks ICM model (discussed above). During the baseline 5 year event, despite both outfalls being submerged for at least 5.75 hours (see Figure 5.5), there is insufficient water trapped within the system to cause surcharging or flooding of any manhole. By submerging the outfalls for

8.75 hours, the 10 year baseline event does cause surcharging of three manholes above of the outfalls (but no water is discharged into the road). However, the attenuation achieved by all four subsequent NFM scenarios during this event mitigates the culvert's water levels such that all surcharging of the urban system is removed.

The baseline cases for the calibration event and remaining design events all result in varying degrees of surface water being discharged from the system onto the estate's main road. The total flood volumes (i.e. summed volumes from all flooded manholes in the network) which result from the baseline case and each of the NFM scenarios are given in Table 5.2.

Table 5.2 Gough Way estate surface flood volumes

Event	Total flood volumes (m^3)				
	Baseline	Wood debris only	Trees Option 1	Trees Option 2	Max-NFM Scenario
Calibration	23.7	10.7	21.6	18.1	8.0
20 Year	2.2	0	0.1	0	0
30 Year	6.5	0	1.4	0	0
50 Year	7.4	0	6.4	3.1	0
100 Year	19.9	0.2	18.1	12.9	0

Table 5.2 shows that the calibration peak event causes substantially more surface flooding than comparable design events. This demonstrates the importance of the particular pattern of each rainfall event. The design events are incorporated as a single pulse of rainfall and surface flooding occurs when a sufficient amount of the resultant urban response is unable to escape through the outfalls. However, during the calibration event the extended rainfall continues to fall on an already surcharged drainage system and this then exacerbates flooding volumes. Despite higher baseline flood volumes, all four interventions reduce flooding – the max-NFM scenario reduces the total volume by 65%.

These reductions contrast with the results presented in Figure 5.5, where the scenarios are shown to have very little effect on the inundation durations during the calibration event. Taken together, Figure 5.5 and Table 5.2 illustrate the importance that de-synchronising rural and urban responses have on resultant surface flood volumes. Alone, the woody debris intervention reduces surface flooding during the calibration period by 55%, despite only reducing the peak magnitude by 2.1%. This contrasts with the tree planting option 2 which, despite reducing the same peak by 14.4%, only achieves a volumetric reduction of 24%. Being much flashier than the rural hydrograph, it is the tail of the urban response which gets trapped by outfall inundation (see Figure 2.6 for an idealised depiction of this). Delaying the rural response allows more water to escape the surface drainage system, increasing the effective capacity of the system. While tree planting does do this to a certain extent, the woody debris intervention is more successful. This desynchronisation phenomenon continues to be effective as storm severity increases, and the max-NFM scenario (which incorporates the tree planting) removes surface flooding from the estate, even in a 100 year event. It is recognised that the methodology assumes uniform rainfall across both rural and urban environments and differing storm tracks would significantly alter resultant drainage performance.

While the rainfall event's timing and pattern will clearly influence upstream NFM's ability to improve drainage performance, the importance of the inundation duration metric should not be discounted. Neither should the benefit of significantly reducing outfall inundation during frequent events when surface flooding does not occur. By improving free discharge from outfalls generally, the system is better prepared for future events. This could come into play during multiple events or extended periods of rainfall. Rather than mitigating severe flood risk, the potential objectives for upstream NFM interventions could be widened to include reductions in nuisance flooding in urban environments.

The impacts of NFM on mitigating surface flooding in the estate need to be qualified with consideration of the fluvial flood risk. The Infoworks model suggests there is fluvial flooding of a nearby main road during the 20 year event, which is removed only by including tree planting option 2 in the upstream intervention. Similarly, fluvial flooding of the housing estate (which is suggested to occur in a 30 year event) is more likely to be mitigated through the peak reductions achieved by the tree planting options. Therefore, when evaluated through the prism of fluvial flooding, the in-channel woody debris intervention would be much less effective. The high risk of fluvial flooding would also eclipse concern that upstream interventions could slightly prolong outfall inundation during severe events (as indicated by Figure 5.5).

5.5 Summary

The results from this initial Bin Brook case study indicate that considering the 'rural-urban' interface could enhance understanding of urban drainage responses and offer potential for improving performance. Elevated river levels preventing discharge from outfalls have been shown to have detrimental impact on drainage performance in the housing estate.

While the ability of NFM interventions to mitigate downstream water levels below the 'inundation threshold' (defined in Figure 2.6) is important, the ability to desynchronise rural and urban responses creates greatest reductions in surface flood volumes. For instance – by delaying rural response by 45 minutes using the max-NFM scenario, the surface flood volume during the 2012 event is reduced by 65% in the downstream estate. Such delays, if only slight, continue to have benefit as storm severity increases (although this should be contextualised by the associated rise in fluvial flood risk). The benefits to drainage, while consistent, appear to be modest. There is no indication that significant surface flood risk could be alleviated, but the results suggest that interventions of the kind modelled here may help mitigate nuisance flooding.

The Bin Brook catchment is intensively farmed, making the hypothesised intervention (shown in Figure 5.1(a)) indicative of significant changes in the catchment's land management practices. The cost and practicality of any implementation would need to be evaluated against the potential benefits. The reduction of isolated instances of downstream nuisance flooding is unlikely to solely justify such interventions on the scale hypothesised. However, Lane (2017) highlights how the literature tends to focus on the 'fluvial flooding' mitigation properties of NFM and that other benefits of interventions need increased recognition (discussed further in section 2.2.3).

This initial case study has provided prima facie evidence that NFM could also improve the effectiveness of downstream surface drainage outfalls. The next case study will apply the methodology to a different catchment, building on these findings to widen the evidence that will inform a response to the central research question.

Chapter 6

Asker River Case Study

6.1 Introduction

This chapter sets out the results from the second case study – the Asker river catchment. The results from modelled upstream NFM interventions on the performance of downstream surface drainage in the town of Bridport are presented. This chapter has a similar structure to Chapter 5.

The results from this chapter have been reported in Ferguson and Fenner (2020b).

6.2 Location

The River Asker drains an area of rural western Dorset, rising from the slopes of Eggardon Hill ($\sim 250m$ above sea level), flowing west for approximately $8km$ before meeting the Mangerton River and flowing through the town of Bridport ($\sim 10m$ above sea level with a population of approximately 14,000). The town of Bridport sits on the confluence of three rivers – the Asker, the Brit and the Simene. The Asker joins the Brit before discharging into the English Channel.

The watershed area studied here covers the contributing area to the urban watercourse running through Bridort – an area of approximately $48km^2$ (see Figure 6.2 for a map) and referred to henceforth as the 'Asker catchment'. The watershed is predominantly grass and pastureland (approximately 62% of total area) with significant pockets of arable (24%) and woodland (8%). There are several sparse villages scattered throughout the catchment (of which Powerstock – population approximately 350 – is the largest). The layout of the catchment is shown in Figure 6.2.

(a) (b)

Figure 6.1 (a) Asker River downstream flow gauge (FG1 in Figure 6.2 (a)) and (b) location of surface drainage outfall (DO1 in Figure 6.2 (c)) [looking downstream]

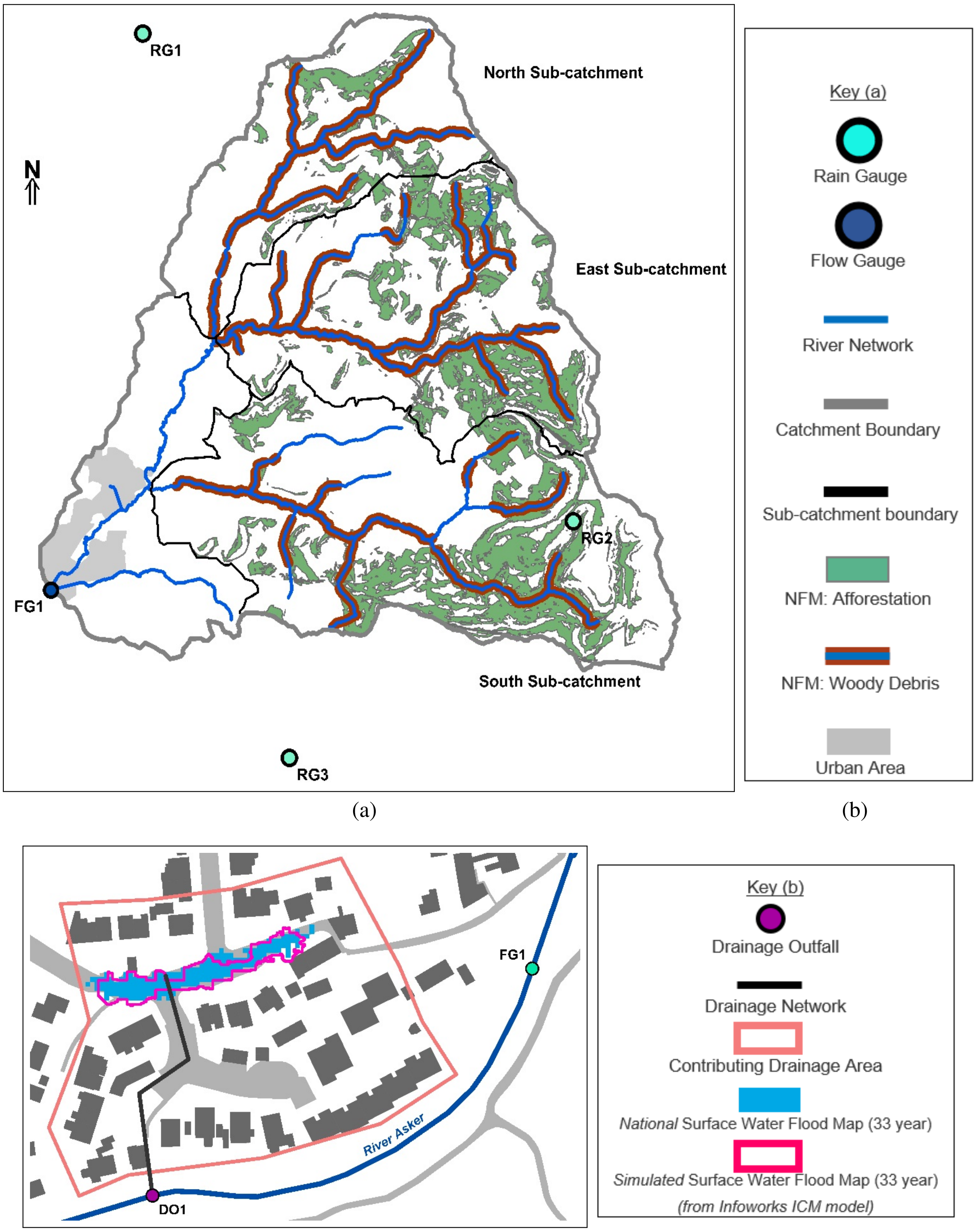
Eggardon Hill, the highest point in the catchment, marks the beginning of chalk groups that stretch away from the catchment along the coast towards the Isle of Wight and the South Downs. The catchment drains from these chalk groups, crossing areas primarily formed of silty mudstone and sandstone, eventually reaching alluvium deposits in the lower river reaches. The soils in the catchment are predominantly shallow (e.g. $< 1m$ depth), although over 95% of the bedrock is classified as having either 'high' or 'moderate' permeability by the British Geological Survey (BGS).

6.2.1 Flood History

While the Brit has caused significant fluvial flooding in recent years (BBC News, 2014, 2016), flood defences (i.e. adjacent banking) built in the 1980s have prevented the Asker overtopping during these events (West and Mann, 1987). However, water levels in the River Asker have influenced surface flooding with drainage unable to cope with intense pluvial events. This is indicated by the updated surface water risk map (UK Government, 2019) within the drainage zone shown in Figure 6.2 (c), At least 10% of the area (primarily the only access road for over 30 residential properties) is affected by surface flooding during a 30 year return period storm.

6.2.2 Available Data

The Asker river is gauged downstream in Bridport with a Flat V Crump weir (see Figure 6.2 for its location and Figure 6.1(a) for a photograph). There is also a level gauge in the



(a) (b)

(c) (d)

Figure 6.2 (a) Map of Asker river catchment showing gauges and extent of hypothesised NFM interventions (b) Key for rural map (c) Map of downstream area contributing to surface drainage (with comparison of modelled flooding extents and extent from national mapping) and (d) Key for urban map

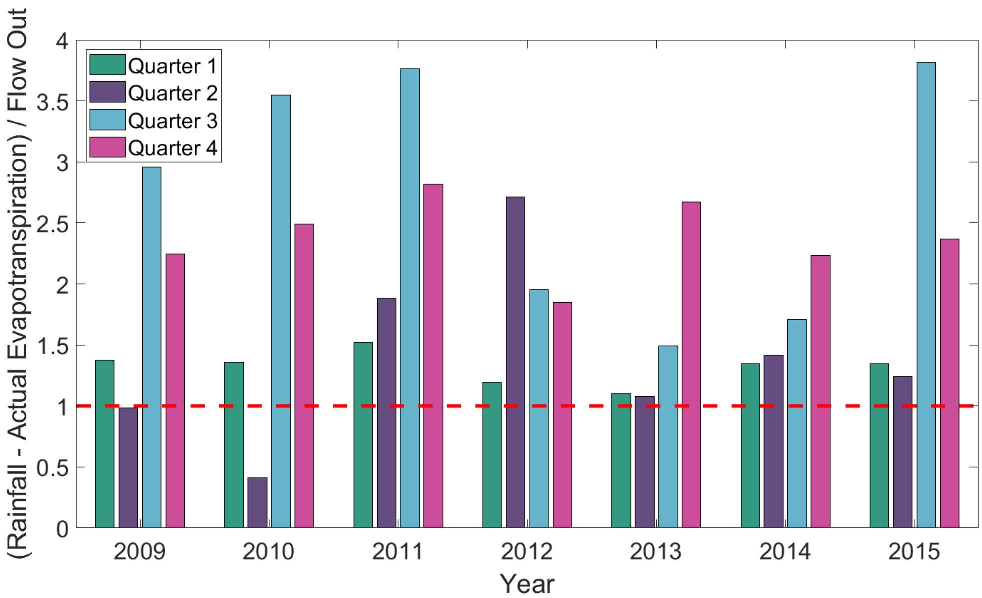


Figure 6.3 Quarterly mass balance for Asker river catchment from 2009 to 2015

uplands without spot rating records (used solely for flood warning systems). The flow record (dating from March 1996 with a 15 minute time step) was obtained from the EA with a FOI request. There is only one EA rain gauge in the catchment. However, two others were within 1.8km of the catchment (see Figure 6.2(a)) and deemed close enough to inform spatial rainfall distribution. These were again obtained with a FOI request to the EA, providing a full record with a 15 minute time step available from February 2008.

The sources for the GIS data layers (for topography, landuse, geology, river network layout) are given in Table 3.5 (all were obtained using a watershed delineated with a 5m DEM using a similar technique to Chapter 5).

A preliminary mass balance check revealed significant and relatively consistent discrepancies in the measured data. Across the seven years shown in Figure 6.3, net rainfall typically exceeds the total mass leaving the catchment through the flow gauge (across quarterly intervals). To make this calculation, rainfall gauge data was spatially extrapolated using Thiessen polygons. Actual evapotranspiration was approximated by converting potential evapotranspiration values from the Centre for Ecology and Hydrology's (CEH) CHESS database (with a record up to December 2015) (Robinson et al., 2016). The limited available data meant this approximation was carried out using a simple sinusoidal function (established by Calder (1986) and implemented using an R function developed by Metcalfe et al. (2015)).

There are several potential contributing factors to explain this mass imbalance. Percolation (or flow through fractured medium) within the bedrock chalk layers in the eastern uplands – although only covering 10% of the catchment area – may be having an influence on the whole-catchment catchment response (the influence of chalk on catchment response has been extensively discussed (Hughes et al., 2011; Jimenez-Martinez et al., 2016)). In essence, there may be differences between the surface and sub-surface catchment boundaries. Although less porous, infiltration into the lower sandstone bedrock (which covers 47% of total area) may also be causing losses to groundwater. These incongruities between the surface and groundwater catchments could be being compounded by a seasonal fresh-saline water boundary, with groundwater discharging directly to the sea. There may also be gauging errors resulting in over-estimation of rainfall input (e.g. through extrapolation across Thiessen polygons, minimum measurement interval or reporting faults). It is also possible there are unknown abstraction flows across the catchment.

One of the key assumptions in Dynamic TOPMODEL – that of approximating the effective hydraulic gradient from the slope angle – means that the model is best suited where catchment response is dominated by response of shallow soils. This limits the ability of the model to characterise the apparently complex sub-surface flows within this case study catchment. However, its strengths (discussed and justified in Chapter 3) make it ideal for the focus of this research – whether upstream interventions can impact on downstream drainage. For this reason, a rainfall correction factor was used to equate the observed mass balance, with losses to groundwater assumed as not affecting surface and shallow sub-surface catchment response. Given that any NFM intervention will have no impact on the behaviour of the underlying bedrock, this was deemed a pragmatic way forward. For the calibration period (across January and February 2014) this meant reducing the rainfall input by a factor of 0.74.

6.3 Model Construction

6.3.1 Calibration

A Monte Carlo procedure was used to calibrate the hydrological model, based on simulations run with a 15-minute time step from 00.15 on 17th January 2014 to 00.00 on 25th February 2014. Similarly to the method set out in Chapter 5, the peak flows within 10% were then ranked based on their replication of the inundation period and the NSE. This parameter set (given in Table 6.1) was then carried forward to the HEC-RAS calibration. This was carried out using the previously described sensitivity analysis, giving a final global roughness value of 0.024. Figure 6.4 compares the final simulation with the flows observed at the downstream flow gauge (labelled FG1 in Figure 6.2(b)). The NSE of this final calibration is 0.83.

Table 6.1 Calibrated Dynamic TOPMODEL parameters for the Asker

Parameter	Units	Value (2 s.f)
$ln(T_0)$	m^2/h	9.3
m	m	0.0036
$s_{rz,max}$	m	0.14
$s_{rz,0}$	$\%$	1
t_d	hr/m	49
v_{chan}	m/hr	1600
v_{of}	m/hr	92

Although the coupled model has captured the maximum flow, the peak magnitudes across the calibration period are generally slightly under-predicted. While the flashiness of these larger events has been mostly replicated, the simulated response is more sluggish for smaller events. The timing of the simulated events has been captured appropriately, though the base flow is under-predicted. Potential reasons for this include: (1) an under-estimation of the soil storage in the model (potentially skewed by the mass balance alterations – see section 6.2.2) and/or (2) insufficient capturing of catchment rainfall through Thiessen polygons and gauges outside the watershed. However, for the purposes of this study, this simulation from the coupled models was deemed an acceptable fit.

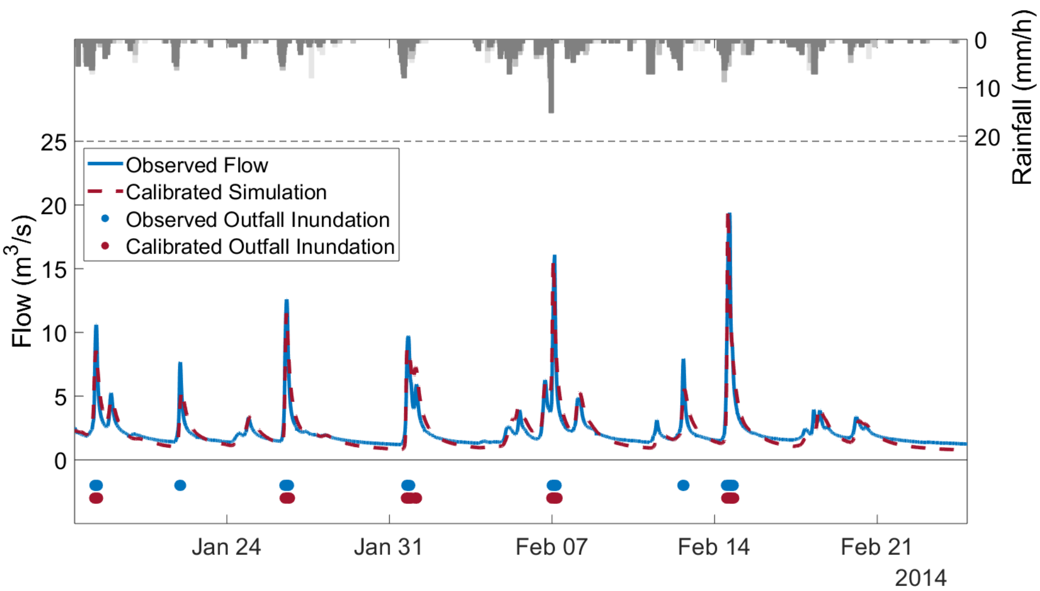


Figure 6.4 Calibration of coupled model and consequent outfall inundation periods when compared with observed flows

An Infoworks ICM model (developed from one provided by Wessex Water – the local water company) was used to model the response of part of Bridport's surface drainage network (see the drainage area outlined in Figure 6.2 (c)). Cross-section data from an EA river model of the Asker (produced in 2013 by JBA) was also inserted into the Infoworks model to allow an integrated numerical replication of the urban drainage system and receiving watercourse flows. This original model was initially unverified. However, after calibrating of the upstream rural response (with Dynamic TOPMODEL and HEC-RAS), a 3.3% AEP year storm was run through the coupled model. The flooding extent from this simulation (caused by surcharged manholes in the drainage zone) is within 2% of the flooding area indicated by the national surface water flood map. A comparison of the two extents (from the coupled model and from the national mapping) is given in Figure 6.2 (c). The model was then deemed as giving an acceptable estimation of drainage behaviour.

Both the observed and simulated upstream rural hydrographs were then fed into the Infoworks ICM model (as upstream inputs), resulting in periods of inundation of the downstream surface drainage outfall (DO1 in Figure 6.2 (c)). These periods of inundation have been defined as occurring when the receiving watercourse rises above the invert of the outfall pipe. For the most part, the simulation has replicated these periods of inundation (see Figure 6.4). Across the 6 week calibration period, there were 28.5 hours of inundation observed, while 24 hours were simulated in the calibration. This slight under-estimation is primarily caused by two smaller events (the flashiness of which were not replicated in the calibration) which caused short periods of inundation.

6.3.2 Intervention

After obtaining the calibration, the tree planting and in-channel woody debris interventions were applied across the three upstream sub-catchments – see Figure 6.2 (a).

Section 3.3.2) justifies the parametrisation of both interventions.

The locations chosen for modelled tree planting were: (1) in areas of existing grassland (2) areas with underlying soils that were either free draining or slowly permeable and (3) locations on slopes between 10 and 30% (which is comparable to other physical studies (Archer et al., 2013; Marshall et al., 2014)). The full extent amounts to $\sim 20\%$ of the total catchment area.

The woody debris intervention intervention was applied in areas of the channel 50m away from any infrastructure such as buildings or bridges (to reflect the wider concern about moving debris blocking culverts and exacerbating flood risk (Curran, 2010)). This amounts to $\sim 61\%$ of the total channel length.

When both interventions are applied simultaneously, there are seven different spatial combinations of such ‘NFM-max’ (as defined in Chapter 5) interventions – three when applied in a single sub-catchment, three with two sub-catchments and another when all three upstream areas have both the interventions applied at the same time.

6.4 Results

The remainder of this chapter will examine the influence of interventions during both (1) the calibration event and (2) a series of seven design storms (10, 15, 20, 25, 33, 50 and 100 year return periods). These design storms (all of which cause downstream outfall inundation) were generated using FEH catchment descriptors and run through the coupled model in order to give a better understanding of the impact of NFM on drainage performance across a wide range of events .

6.4.1 Impact on Flow

Figure 6.5 shows the impact of the seven different spatial combinations of max-NFM intervention (described in section 6.3.2) on the three largest flow peaks within the calibration

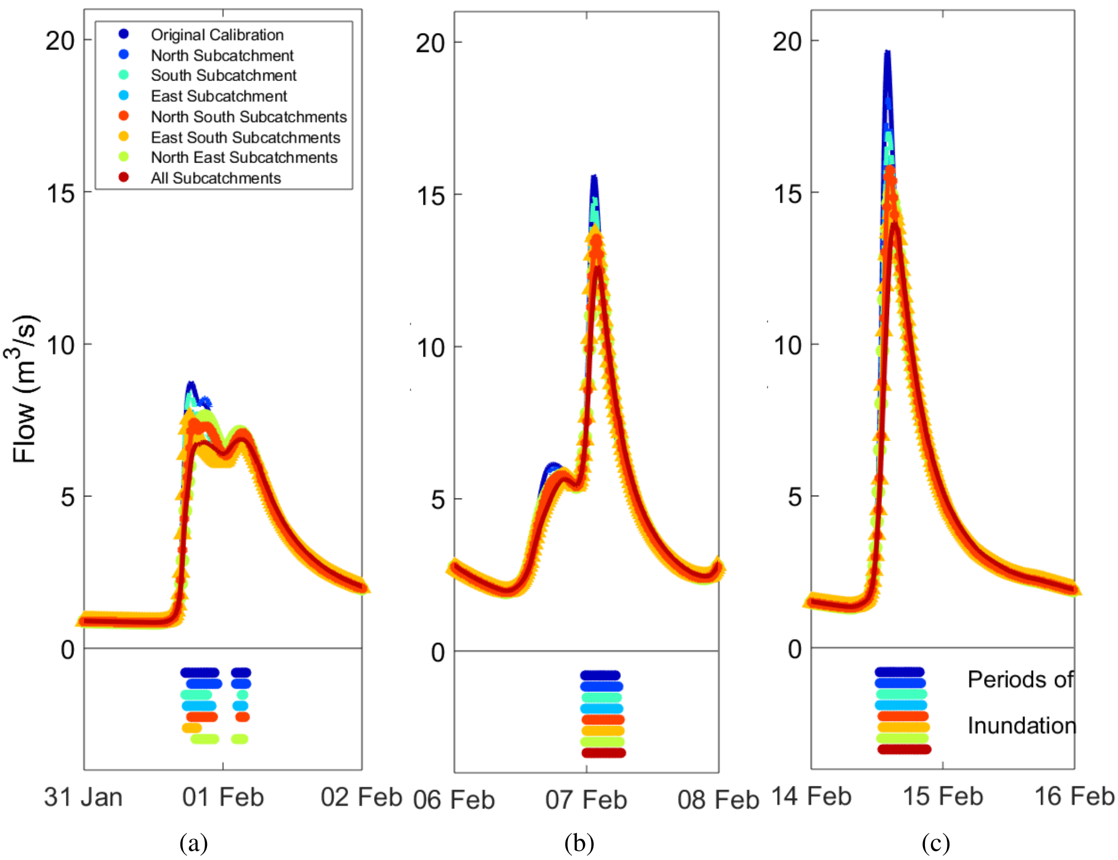


Figure 6.5 Impact of max-NFM scenario in targetted sub-catchments during (a) Peak Period 1 (b) Peak Period 2 and (c) Peak Period 3

period. All combinations reduce peak magnitude. In general, the more sub-catchments targeted with NFM, the greater the reduction. A single altered sub-catchment can decrease peak flows across this calibration period by anywhere between 4% and 10%. With two upstream areas this jumps to between 12% and 26%. With interventions across all three, peaks reduce between 19% and 28%. The base flows between these peaks saw minimal impact from any intervention.

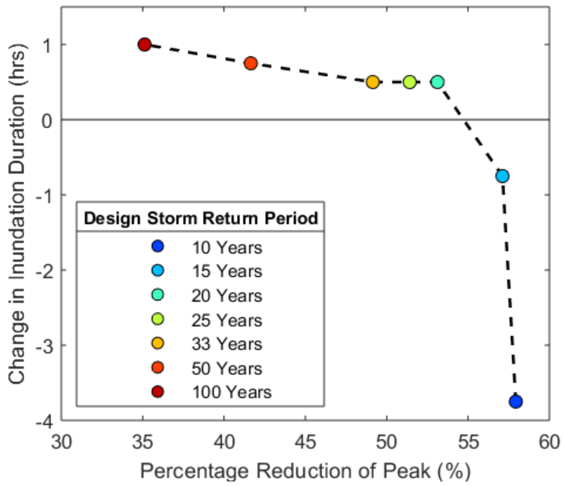
To understand more about the individual contributions of the two different forms of NFM, each one was run through the coupled model for every design storm. Figure 6.6 (b) compares these individual contributions (when applied across all three sub-catchments) against the combined, overall peak flow reduction. As expected, peak reductions diminish with increasing storm severity. However, even for a 1 in 100 year storm, cross slope planting and woody debris cause 15% and 27% reductions respectively.

6.4.2 Impact on Outfall Inundation

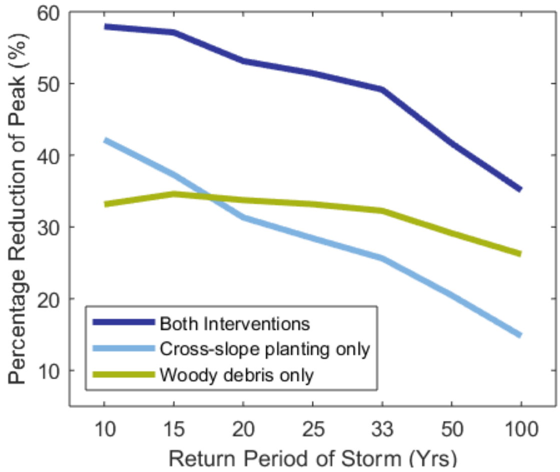
Figure 6.5 also shows that, through attenuation of the hydrograph, these interventions are impacting the time water-levels remain above the downstream outfall. The smallest peak (1st February) sees the greatest impact – with all intervention combinations reducing the time the downstream outfall is inundated (which in the plain calibration was 7.25 hours). The north and east interventions reduce this period by 30 and 90 minutes respectively. The south intervention has a substantially larger individual impact, causing a reduction of 2.75 hours. Two sub-catchments have a wider range of improvement- reducing the inundation period to between 2 and 5 hours (the most effective being the east-south combination). When all three have interventions, the model suggests that inundation is removed entirely. However, the two later peaks (on 7th and 15th February) do not see such positive impact.

In fact, the attenuation of the larger peaks mean that inundation durations are either unaltered or even prolonged slightly. The model suggested the largest intervention could prolong inundation from the middle and largest peaks by 45 minutes.

Figure 6.6 (a) compares peak reductions to changes in inundation duration for seven separate storms with tree planting and woody debris present across all three sub-catchments simultaneously. This intervention lessened peak magnitude for the 10 year storm by 57% and also reduced the inundation by 3.75 hours. The impact on peak flow for the 15 year storm is similar, but the reduction in inundation is much smaller – 0.75 hours. For larger events (from 20 year returns) peak reductions remained significant but there were slight increases in the time that the outfalls were submerged (of 15 or 30 minutes).



(a)



(b)

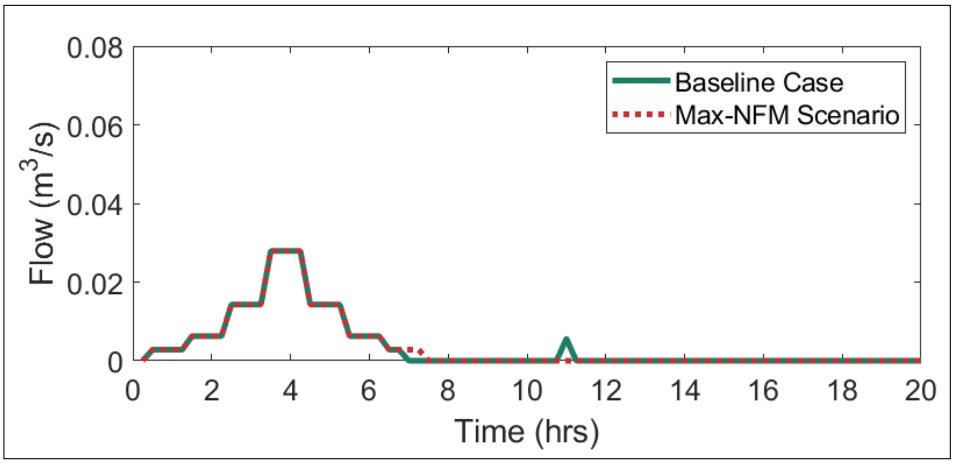
Figure 6.6 (a) Impact of the max-NFM scenario (across all three sub-catchments) on peak magnitude reduction and change in outfall inundation for a series of design storms and (b) Impact of individual interventions (applied across all three sub-catchments) on the design storms

6.4.3 Impact on Drainage Performance

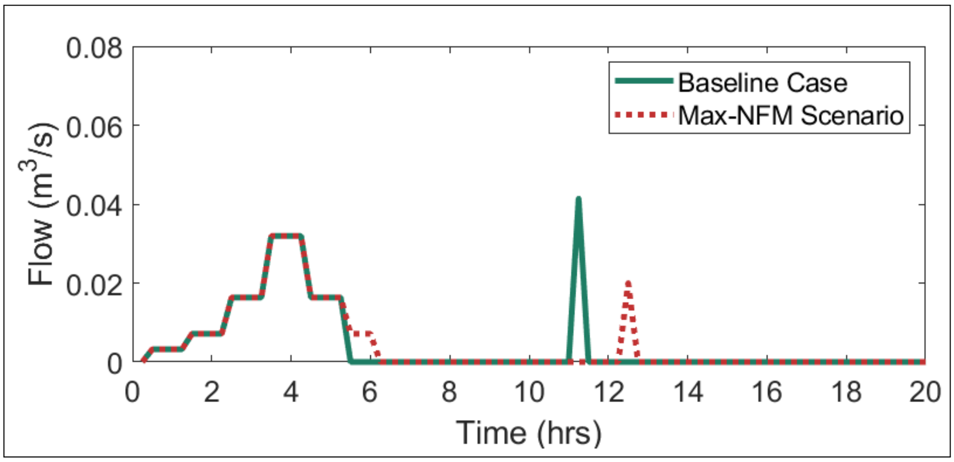
Figure 6.7 compares the output hydrographs from the drainage outfall DO1 (see Figure 6.2 (c)) during three baseline design storms and with the subsequent NFM scenario.

The figure demonstrates that the design rainfall dominates the downstream flow profile throughout much of the design storm. This is due to the lack of dispersion through the small and flashy drainage response.

The inundation of the outfall (and consequent prevention of discharge) commences in the latter stages of the rainfall event. Comparison of the three sub-figures illustrates that the more severe the event, the earlier the outfall is inundated. For the baseline 10 year event, this causes a small portion of time when flow cannot escape and is held inside the pipe until the rural response has passed the outfall. This gives rise to the small secondary spike. Under the max-NFM scenario, the inundation of the outfall is completely removed. Figure 6.7 (b) demonstrates how the earlier inundation during the baseline 20 year event (along with the greater rainfall intensities) means greater volumes of surface water are trapped within the urban system. This results in a much larger later spike as this surface water escapes once the rural hydrograph has passed beyond the drainage outfall. The same figure shows that the attenuation from upstream NFM allows more water to escape the system before outfall inundation, thus making the secondary spike smaller.



(a)



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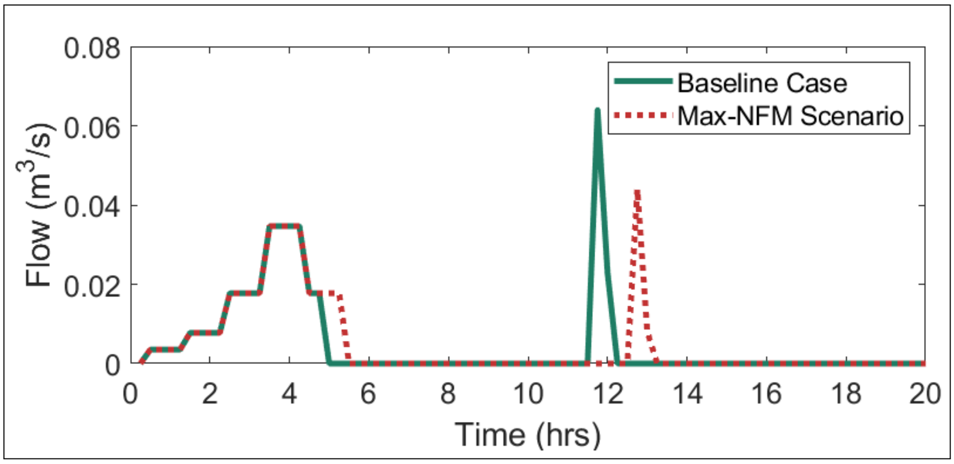


(c)

Figure 6.7 Discharge from Bridport drainage outfall DO1 during (a) 10 year design storm (b) 20 year design storm and (c) 33 year design storm

During the 33 year event (Figure 6.7 (c)), similar behaviour is seen. The baseline latter spike is larger because of the greater volume of water held within the pipe. The reduced attenuation of the rural hydrograph from the upstream NFM scenario (compared with the more frequent events) means that the two latter spikes are closer together.

Figure 6.8 demonstrates the ‘before’ and ‘after’ flooding extents from manholes in the Infoworks ICM model to show the impact of NFM on performance of the surface drainage network. In the unaltered catchment, the 10 year storm led to inundation of the network, without causing surcharging into the estate. However, the upstream NFM intervention removes any surcharging within the urban system. The 15 and 20 year storms cause surface flooding in the estate (of differing extents). In both cases, the upstream intervention removes any surface flooding, although the system remains surcharged. Although there is still street flooding in the 33 year storm, the upstream interventions significantly reduce the maximum extent. This is very interesting because in Figure 6.6(a) the 20 and 33 year storms are shown to prolong the time the outfall is submerged. In fact, the attenuating impact of the interventions is delaying the pulse in the receiving water course, meaning more water can escape the urban system before the rural response submerges the outfall.

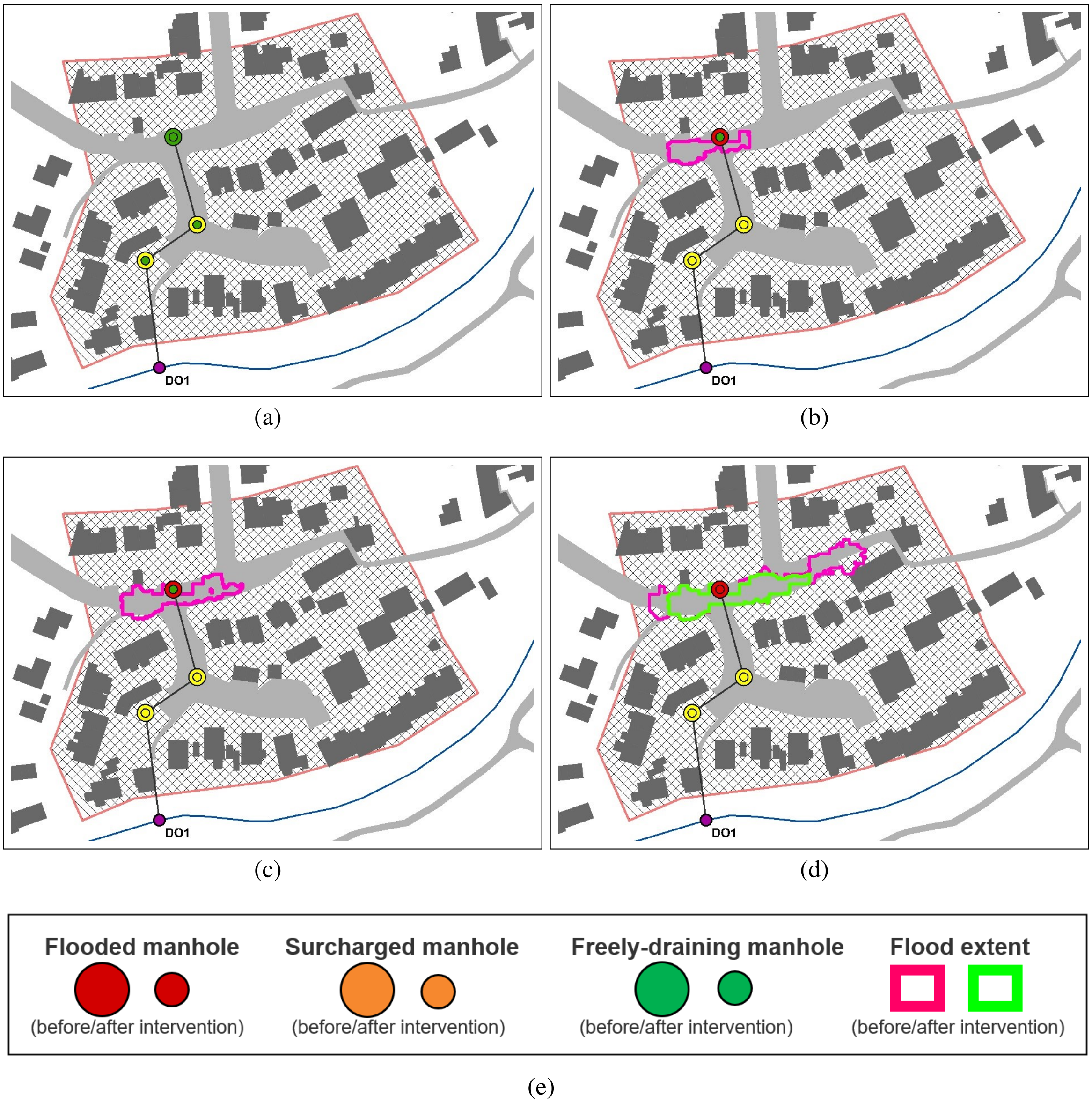


Figure 6.8 Surface flooding extents of Bridport surface drainage network under (a) 10 year event (b) 15 year event (c) 20 year event (d) 33 year event

6.5 Discussion

NFM interventions are broadly successful in reducing the magnitude of peak flows in the River Asker during the calibration period (Figure 6.5). The peak attenuations also reduce inundation of the Bridport outfall, albeit within a more limited range of smaller events (up to a 1 in 20 year storm - from Figure 6.6 (a)). This gives encouragement that other catchments, especially those containing frequently submerged outfalls, might also benefit from upstream interventions over that kind of window of smaller events.

It is also interesting to note that each combination has a different impact on the calibration peaks. For example, the interventions in the north sub-catchment achieve the largest impact for the second peak but the smallest impact for the third. It is hypothesised that this results from the spatially varying rainfall (through the Thiessen polygons discussed earlier) influencing sub-catchment response. In the literature, the role of tributary timing on downstream response has been acknowledged as a determining factor of downstream response (Pattison et al., 2014). However, in this case, there was no strong correlation between upstream interventions desynchronising tributaries and subsequent greater downstream reductions.

Figure 6.6(b) demonstrates the effectiveness of two interventions individually and that, for more frequent storms, afforestation of the catchment's slopes has greater impact. However, the figure also shows the woody debris intervention is more effective in more severe storms. This could be because the increased flows do not translate to proportionally greater water depths in the HEC-RAS model (given the river channel geometry is not explicitly considered). It should also be noted that no consideration for failure or movement of woody debris has been made, and this would become increasingly likely in severe storms. Figure 6.6(b) also shows that, for every design storm, the sum of the two individual intervention reductions is greater than the reduction seen when they exist together in the catchment model. It is hypothesised that the attenuation caused by the tree planting intervention is improving the ability of the woody debris to attenuate flows within the channel.

The results in Figure 6.8 are encouraging. By reducing the likelihood of manhole surcharge during a 1 in 10 year storm, upstream NFM is maintaining the effective capacity of the drainage network, thereby reducing risk of surface flooding from future storms. It has been recognised that improving the ability of a system to recover and prepare for further events makes the system more resilient (Bhattacharya-Mis and Lamond, 2014). Despite extending the duration of inundation, the interventions also have a positive impact on the system in more severe storms by reducing the amount of water discharged onto the roadway. This shows that both the duration and timing of the inundation period are critical in how upstream interventions impact downstream drainage functionality (particularly in larger events). Any de-synchronisation (of the river and drainage responses) would be reliant on the relative timing of the rainfall and therefore the storm track across the catchment. However, it should also be noted that with the increasing storm severity, the evidence behind intervention impact is weaker (Dadson et al., 2017) and, in general, other flooding mechanisms will become dominant (e.g. fluvial). The residential area focused on in Bridport experiences fluvial flooding from the 50 year event onwards (see section 9.4 for further discussion on this). It could also be argued that, although interventions are having a positive impact on a single storm, the consequence of prolonging the outfall being drowned means that the overall system is less resilient to further rainfall (i.e. in multiple events). There are also other discharges into the Asker River from Bridport and differing local outfall geometries will result in different responses to upstream interventions.

The results in Figure 6.8 assume a uniform rainfall across both rural and urban catchments. Given the flashiness of the urban response, this assumption has a large bearing on the extent of subsequent surcharging of the drainage network. Differing storm tracks will alter the relative timing of the two responses, potentially creating wider (or reduced) surface flooding. Evaluation over a wider range of storm scenarios would provide a more detailed understanding of the mitigating effects of the selected NFM interventions. This idea is developed further in section 8.3.

6.6 Summary

The case study results have indicated that significant upstream interventions in the Asker catchment have the potential to attenuate peak flows by up to 28%. Results also suggest that these interventions could reduce the duration that drainage outfalls are submerged during frequent events (up to 1 in 20 year storms) and this has been shown to improve the resilience of the urban surface water system. However, in larger events (e.g. beyond a 30 year return period), the impact is more nuanced with upstream interventions promoting discharge from the system despite also slightly prolonging inundation of the outfall.

While this is encouraging, it should also be recognised these results are based on a calibration period where the rainfall input has been corrected to ensure an equitable mass balance through the catchment (the reasoning and justification behind this are provided in section 6.2.2). The calibration could therefore be under-estimating infiltration rates across the catchment, meaning impact from physical tree planting could be reduced. Different net rainfall intensities could also change tributary timings and the impact of woody debris on downstream peaks.

The paper has also shown that any such benefit will be highly specific to the nature, location and combinations of any NFM interventions as well as to the multi-dimensional physical characteristics of that particular river catchment. It follows that any new physical local NFM project that includes achieving more secure downstream drainage as one of its objectives would be likely to achieve optimum impact if based, in part, on a preliminary modelling exercise similar to that described above.

Chapter 7

Upper Calder Case Study

7.1 Introduction

Chapters 7 and 8 presents the results from the final case study - Todmorden and an area of the upper Calderdale. As mentioned in Chapter 4, Todmorden is also the lead case study for this research. That is partly because of its size, complexity and the scale of its flood history. However, it is also because it is the subject of additional study. The results are therefore spread over two chapters. This chapter sets out the equivalent results to those in the first two case studies and therefore follows a similar structure to those for chapters 5 and 6. Chapter 8 will describe further modelling and analysis of important variables which have a direct relevance to the central research question.

The results of this chapter have been presented in Ferguson and Fenner (2020c).

7.2 Location

The Upper Calderdale (or the Calder Valley), in West Yorkshire, is characterised by steep sided valleys cutting into the high moorland of the Pennines (Calderdale Council, 2018). Most towns and major infrastructure links sit on the valley floors, often alongside watercourses which drain eastward towards Dewsbury and Wakefield before joining the Aire downstream of Leeds. One of these towns is Todmorden, a market town with a population of approximately 16,000 located at the confluence of the River Calder (which at this point has an upstream contributing area of approximately $20km^2$) and the Walsden Water (approximately $27km^2$). The former, which is the focus of this chapter, is gauged in Todmorden - the contributing area to this gauge is shown in Figure 7.1.

Like much of the UK's uplands, the catchment has a history of overgrazing which has caused the moorland to recede and be replaced with large areas of grassland. The flat-floored valley contains several urban areas (as well as Todmorden), the Burnley Road (a key traffic artery) and rail links that cross the Pennines. The industrial history of the Todmorden area means that, in urban areas, the River Calder is heavily engineered channel acting as a receptor for both (i) tributaries draining off the uplands and (ii) the surface drainage of the urban area. Several reaches are routed under roads, properties and commercial buildings, with culverted sections reaching $\sim 70m$ in places. In certain sub-catchments (not the case study catchment evaluated here), the response is significantly influenced by the Rochdale canal.

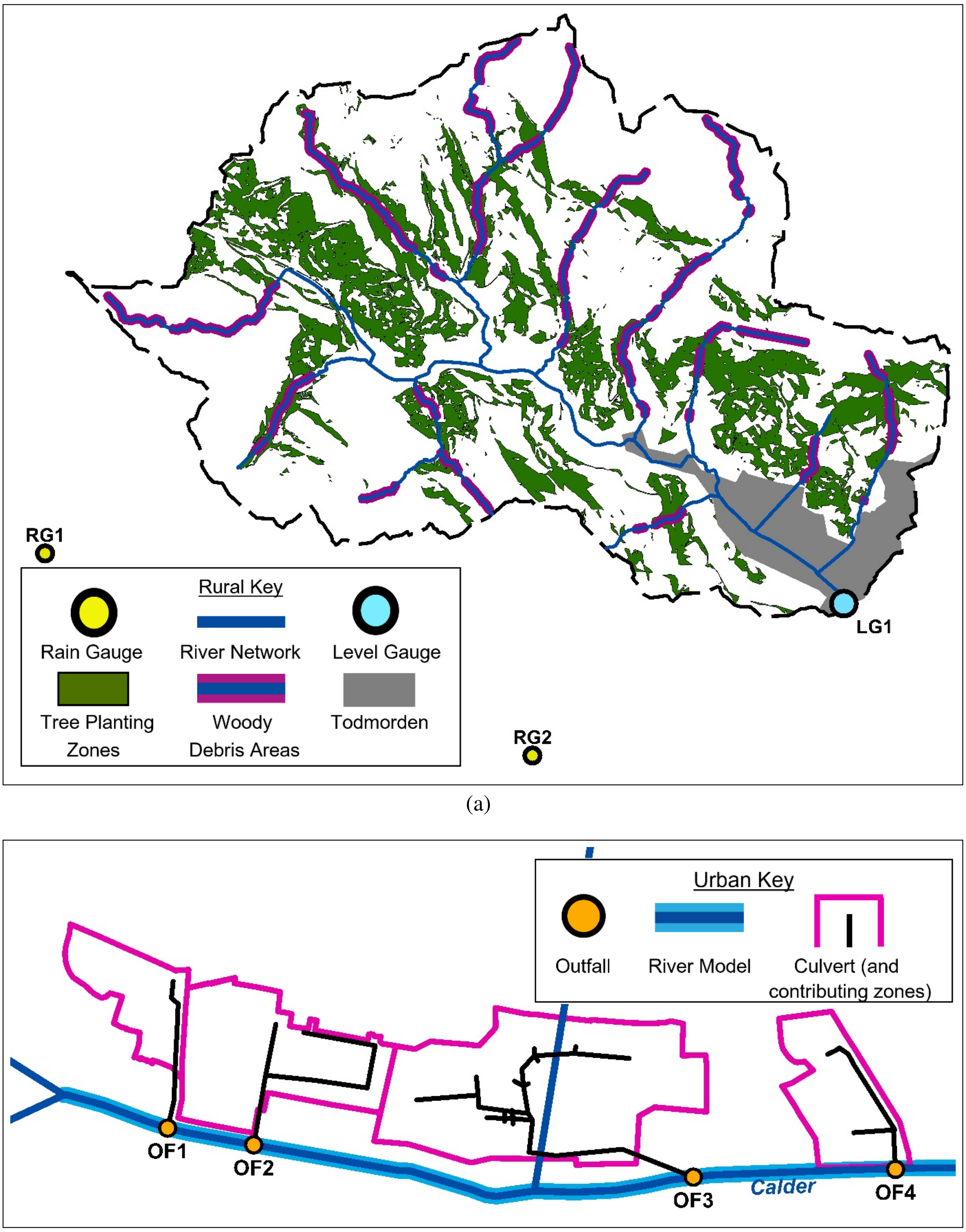
According to the British Geological Survey (BGS), the catchment valley is predominantly formed by layers of sandstone, siltstone and mudstone – in the uplands there are small areas of superficial peat deposits. The catchment has predominantly shallow soil layers (less than $1m$ deep), although there are deeper areas along the valley bottom.

7.2.1 Flood History

There is a long and complicated flood history in Todmorden and Walsden that has been well documented throughout the 21st Century. This had primarily fluvial, pluvial and surface sources (although groundwater flooding is acknowledged as a risk) (Calderdale Metropolitan Borough Council, 2016a). There have been approximately 16 events in the surrounding area since 2001.

In June 2012 there was significant fluvial flooding after more than a month's rainfall during 24 hours – 270 properties were affected (220 of which were residential) (Calderdale Council, 2013). There was also surface water flooding reported on the Burnley Road resulting from overwhelmed drainage. The surface drainage systems in this area (which are the focus of this study – see Figure 7.1 (b)) are designed for a 1 in 2 year event (Calderdale Metropolitan Borough Council, 2016a).

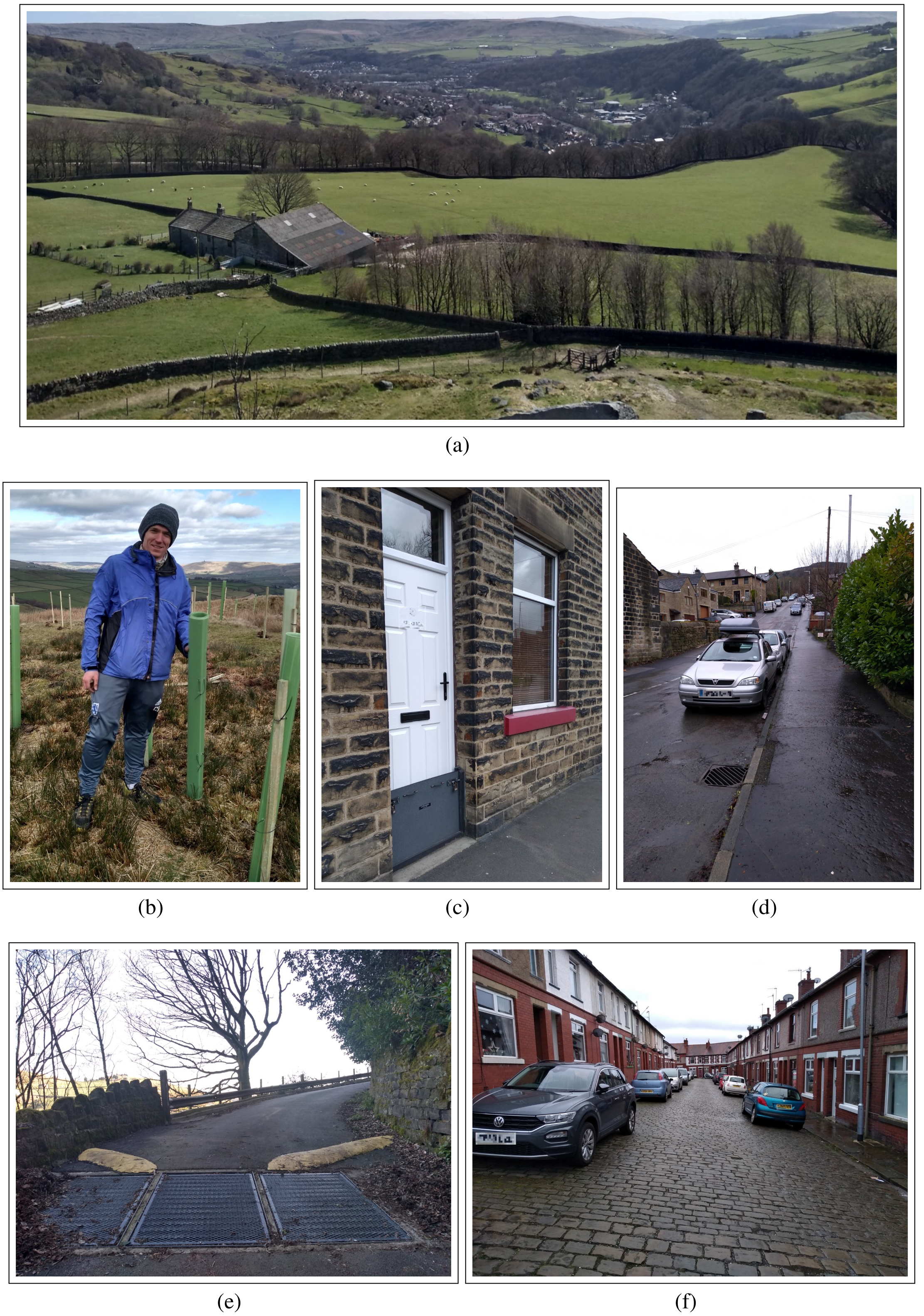
During December 2014, several days of sustained rainfall led to surface water flooding of 9 residential properties across Todmorden and widespread flooding on roads, At no point did the Calder burst its banks, and the primary mechanism was attributed to 'overloading of land drainage'. Indeed, the local flood risk management strategy explicitly states that one key mechanism is "flooding caused by the inhibition of surface water outfalls to the river during high Main River flows." (Calderdale Metropolitan Borough Council, 2016a). Calderdale was the UK's worst affected borough during the Boxing Day 2015 floods, with over 2500 properties affected by various mechanisms (Calderdale Metropolitan Borough Council, 2016b).



(a)

(b)

Figure 7.1 (a) Map of the Upper Calderdale (b) Map of urban drainage



(a) (b) (c) (d) (e) (f)

Figure 7.2 (a) Looking southwards across the study catchment down towards Todmorden in the distance (b) Tree planting implementation in the upper Calderdale (c) property level protection in the urban drainage area (d) Topographic slope of system contributing to Outfall 1 (see Figure 7.1) (e) surface water capture in peri-urban zone of the study catchment and (f) high property density in urban area contributing to Outfall 2 (see Figure 7.1)

Todmorden currently has 2124 houses in Flood Zone 3 (at risk from a storm with a greater than 1% AEP) (Calderdale Council, 2018). The area is set for further growth (with a minimum annual housing requirement of 840 new houses until 2023). As part of this, there are 348 allocated new housing sites around Todmorden. Supporting this growth is extremely challenging given the lack of suitable sites available that are not susceptible to flooding and do not exacerbate risk elsewhere in the town (Calderdale Council, 2018). There have since been further events in the Calderdale, for instance in February 2020 when two separate events caused significant fluvial flooding which affected approximately 500 homes and 400 businesses in the downstream towns of Hebden Bridge and Mytholmroyd (BBC News, 2020). During these events, surface flooding again occurred in the drainage area focused on this study, with local residents identifying a combination of surface runoff and poorly performing drainage as causes for domestic property flooding (Pidd, 2020).

Figure 7.3 Surface flooding within the Todmorden drainage zones given in Figure 7.1 (from Pidd (2020))

7.2.2 Available Data

Topographical, land use, water network and potential evapotranspiration data all came from the sources given in Table 3.5 (similarly to the previous two case studies). There is no rainfall gauge within the watershed. There are, however, two gauges in neighbouring catchments (see Figure 7.1), with a record dating back to July 2004 and a 15 minute time interval. These were used to create a rainfall input based on Thiessen Polygons.

The primary function of the river level gauge (LG1 in Figure 7.1) in Todmorden is to contribute to a downstream flood warning system, meaning the EA has no spot flow records with which to construct a rating curve. However, the highly engineered compound section at the gauging point has been surveyed by the EA (and visually inspected as part of this research project), meaning Manning's equation can be used to convert levels into flows. The rating curve data is given in Appendix B.

The data for Todmorden's drainage system comes from a validated Infoworks ICM model provided by Yorkshire Water (and enabled with a licence from Innovyze UK). Survey data from an Environment Agency river model was incorporated into the Infoworks drainage model to provide an integrated numerical representation of the receiving river reach, outfall and contributing urban system. The height of each outfall invert above each associated channel section invert is given in Figure 7.4

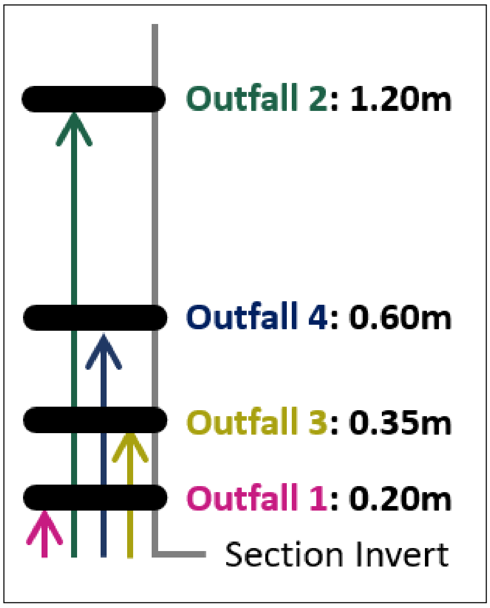


Figure 7.4 Heights of each Todmorden outfall above the channel invert

7.3 Model Construction

7.3.1 Calibration

The coupled Dynamic TOPMODEL and HEC-RAS model was calibrated with a 15 minute step between 07:00 on the 2nd October 2017 and 23.45 on the 3rd December 2017. This period was chosen because it was recent, contains significant magnitudes (i.e. the second largest on record after the 2015 Boxing Day floods) but did not cause widespread fluvial flooding (important given the study's focus on surface flooding). A Monte Carlo approach to calibration was used, with 5000 Dynamic TOPMODEL parameter sets run with the sampling ranges given in Table 3.6. The resultant simulations were evaluated based on both (1) Nash Sutcliffe Estimation and (ii) replication of the three largest peak magnitudes. The final calibrated values are given in Table 7.1 The subsequent HEC-RAS model was calibrated by performing a global roughness sensitivity analysis using the most successful Dynamic TOPMODEL parameter set as an upstream input. The underlying Manning's n value was altered between 0.025 and 0.04 (at 0.001 increments), with a final value of 0.032 offering the best fitting model.

Figure 7.5 compares the final calibration with the observed flows at gauge LG1. Both peak magnitude and timing are extremely well predicted, as is the flashiness of the peaks. The base flows and several of the smaller peak magnitudes are under predicted (which may be a result of the approximated rating curve). Nevertheless, across the whole period, the NSE of the calibrated model output was 0.83 and was a deemed a suitable fit.

Table 7.1 Calibrated Dynamic TOPMODEL parameters for the Asker

Parameter	Units	Value (2 s.f)
$ln(T_0)$	m^2/h	5.1
m	m	0.0064
$s_{rz,max}$	m	0.11
$s_{rz,0}$	$\%$	1
t_d	hr/m	18
v_{chan}	m/hr	1600
v_{of}	m/hr	85

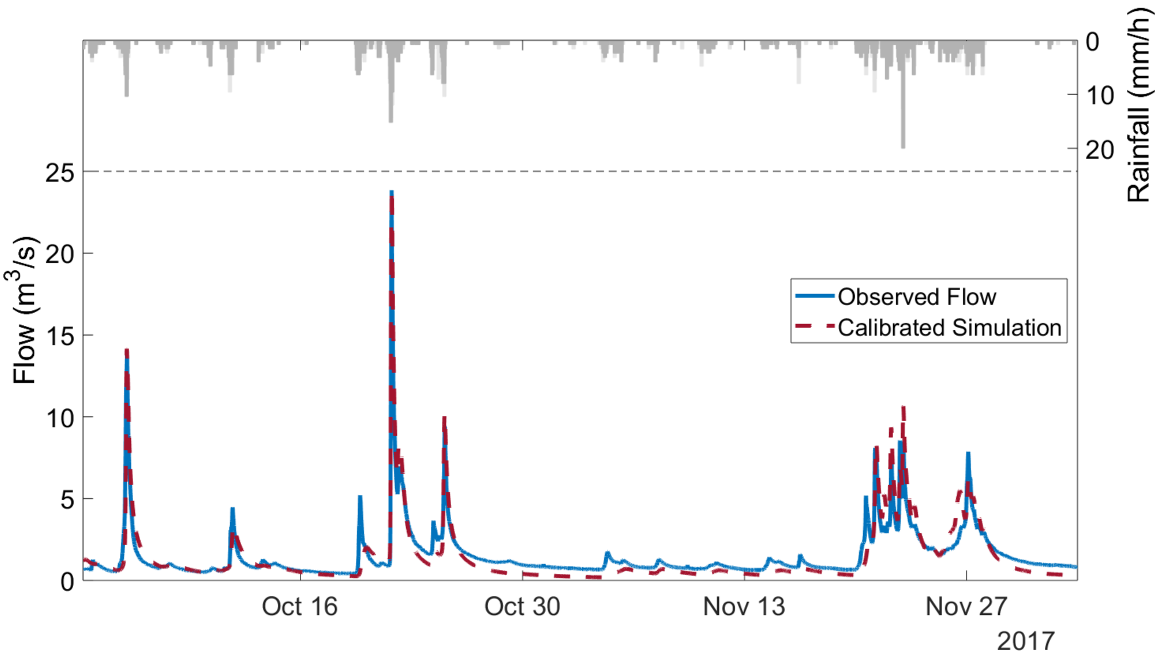


Figure 7.5 Calibration of coupled Dynamic TOPMODEL and HEC-RAS model for the upper Calder catchment

7.3.2 Intervention

While the catchment has no significant NFM implementation projects currently underway, the recent flood history has fuelled projects across the upper Calderdale area. Adjacent to the case study catchment is a watershed containing the nationally recognised Gorpley Reservoir restoration project. This project involves Yorkshire Water, in partnership with local organisations such as Treesponsibility, restoring over 30 hectares of peat, installing leaky dams and fascines as well as planting over 68 hectares of woodland (Spring Partnership, 2018). Treesponsibility are also involved in a large woody debris intervention in nearby Hardcastle Crags (above Hebdon Bridge) (Bradshaw, 2016). Another indicator of the local interest in and support for NFM in the area is the Calderdale Council's dedicated 'NFM Project Officer' position (the second LLFA in the country to have one) and their current grant scheme of £500,000 for local landowners to implement projects across the borough.

The two interventions implemented throughout this research project (tree planting and large woody debris – see section 3.3.2) reflect physical implementation projects across the upper Calderdale.

Desk and walkover studies were used to identify areas for potential tree planting as mildly sloping grassland (between 10 and 30%) across the catchment. This area amounts to 23%

of the total catchment area and the extent is shown in Figure 7.1. The large woody debris intervention (with implementation as discussed in section 3.8.2) was applied along reaches of the channel that (a) are more than 50m upstream of any road bridge and (b) in areas with less than 40% slope.

7.4 Results

Similarly to the previous case studies, the calibrated model was used to evaluate the impact of the NFM interventions during both the calibration period and under a series of design storms. As before, the two forms of NFM are applied as fully matured interventions, with the 'max-NFM' scenario referring to simultaneous implementation.

7.4.1 Impact on Calibration Period

Figure 7.6 illustrates the impact of the max-NFM scenario and its two individual components (the tree planting and large woody debris) on three separate peaks within the calibration period. Applying the woody debris intervention alone within the coupled model reduces peak magnitudes by 3.2%, 2.8% and 2.2% across Peak Periods 1, 2 and 3 respectively. The tree planting causes greater reductions: 8.7%, 7% and 3.9%. Although these reductions are modest, Peak Period 2 contains an estimated 1 in 20 year storm and together the interventions (i.e. the max-NFM scenario) reduce the modelled peak by 8.5%. Peak Period 1 is less severe and the amalgamated interventions have a greater impact of 10.9% peak reduction. The impact of interventions on the intermittent base flows is negligible.

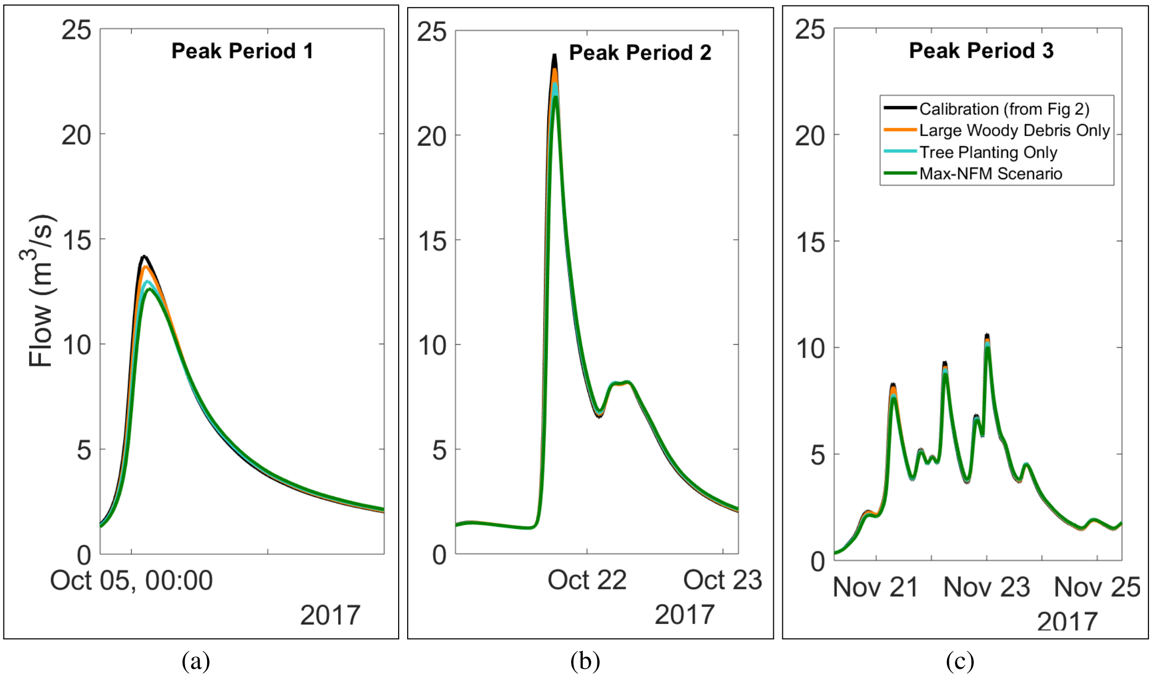


Figure 7.6 Attentuation resulting from tree planting, woody debris and the max-NFM scenario during (a) Peak Period 1 (b) Peak Period 2 and (c) Peak Period 3 of the calibration

Table 7.2 Periods of Inundation for four Todmorden outfalls (during three peaks in the calibration) for the calibration and max-NFM scenarios

	Outfall Inundation periods (hrs)					
	Peak Period 1		Peak Period 2		Peak Period 3	
	Calibration	Max-NFM	Calibration	Max-NFM	Calibration	Max-NFM
Outfall 1	3.75	3.25	6	6	1.25	0
Outfall 2	–	–	1.5	0.75	–	–
Outfall 3	2.75	2.25	4.75	4.75	–	–
Outfall 4	1	0	4.25	3.75	–	–

Table 7.2 demonstrates how these peak reductions translate into changes in the inundation periods of the four outfalls (shown in Figure 7.1 (b)) for both the plain calibration and the max-NFM scenario.

The table indicates that the larger the storm, the more outfalls are inundated and the longer inundation lasts. Generally, there appears to be a small (but reasonably consistent) benefit to the downstream sub-systems – indeed during the largest event (Period 2), the inundation period is halved for Outfall 2. However, during the same event, Outfall 1 (only several yards upstream) sees no change in the 6 hours it is inundated. For two cases when outfalls are drowned for a short time (1 and 1.25 hours), inundation is completely removed. It would appear that any downstream impact from the max-NFM scenario on inundation periods is dependent on event magnitude and local outfall geometry, but it is worth noting that the intervention does not prolong the time any outfall is submerged.

Changing the time outfalls are submerged has consequences for the contributing surface drainage networks. Figure 7.7 presents the results from the Infoworks ICM model during Periods 1 and 2. As indicated by Table 1, Outfall 1 is the most susceptible to flooding. Drowning this outfall for 3.75 hours during Period 1 causes $21.7m^3$ of flooding. Despite the max-NFM scenario reducing this inundation by 0.5 hours, the flood volume only drops to $18.6m^3$. The submersion of Outfall 3 during Period 1 (2.75 hours) causes inundation of the contributing system but does not cause flooding. The inundation of Outfall 4 during Period 1 (which was then removed by the NFM) has no impact.

The longer inundation durations during Period 2 have greater detrimental impact on the four sub-systems. Three sub-systems cause surface flooding (with Outfall 1 again the worst affected). Interestingly, the impacts of max-NFM on the wider sub-systems are greater here (despite smaller peak magnitude and inundation reductions). The flood volumes in the systems above Outfalls 1, 3 and 4 are reduced by 20%, 100% and 25% respectively. Also, the reduction in inundation of Outfall 2 means that surcharging of the sub-system is removed.

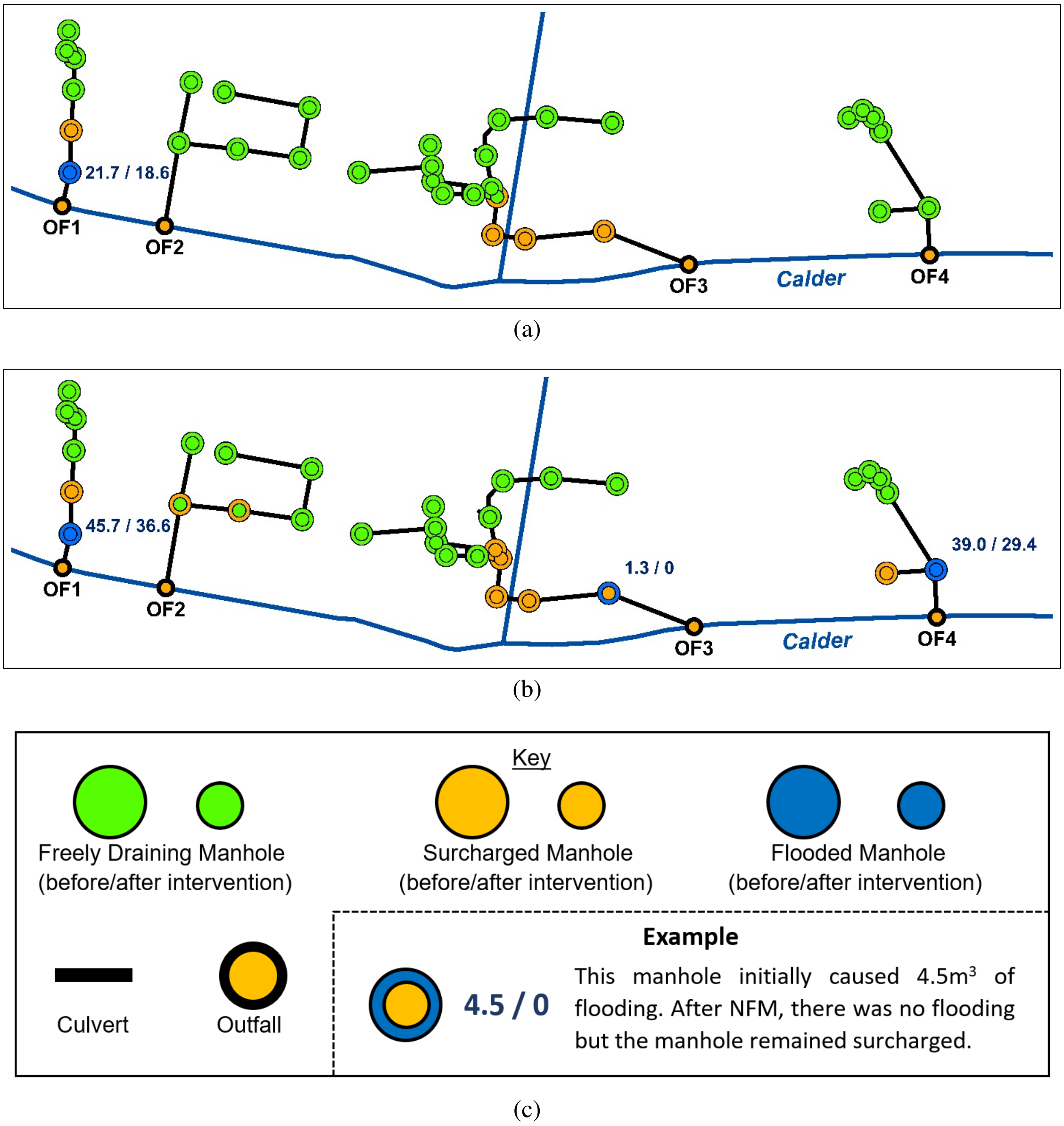


Figure 7.7 Impact of the upstream max-NFM scenario on Todmorden's surface drainage network during (a) Peak Period 1 and (b) Peak Period 2. Figure 7.7 gives the key (for this figure and future similar drainage performance figures)

7.4.2 Impact on Design Storms

A series of design storms (with 10, 20, 30, 50 and 100 year return periods) were then run through both the calibrated plain catchment and the same max-NFM scenario. Each design storm was applied uniformly across both the rural and urban catchments. Figure 7.8 compares the baseline catchment response with the max-NFM scenario. As storm severity increases, the peak reductions from the NFM diminish from 15.1% (10 year) to 7.2% (100 year).

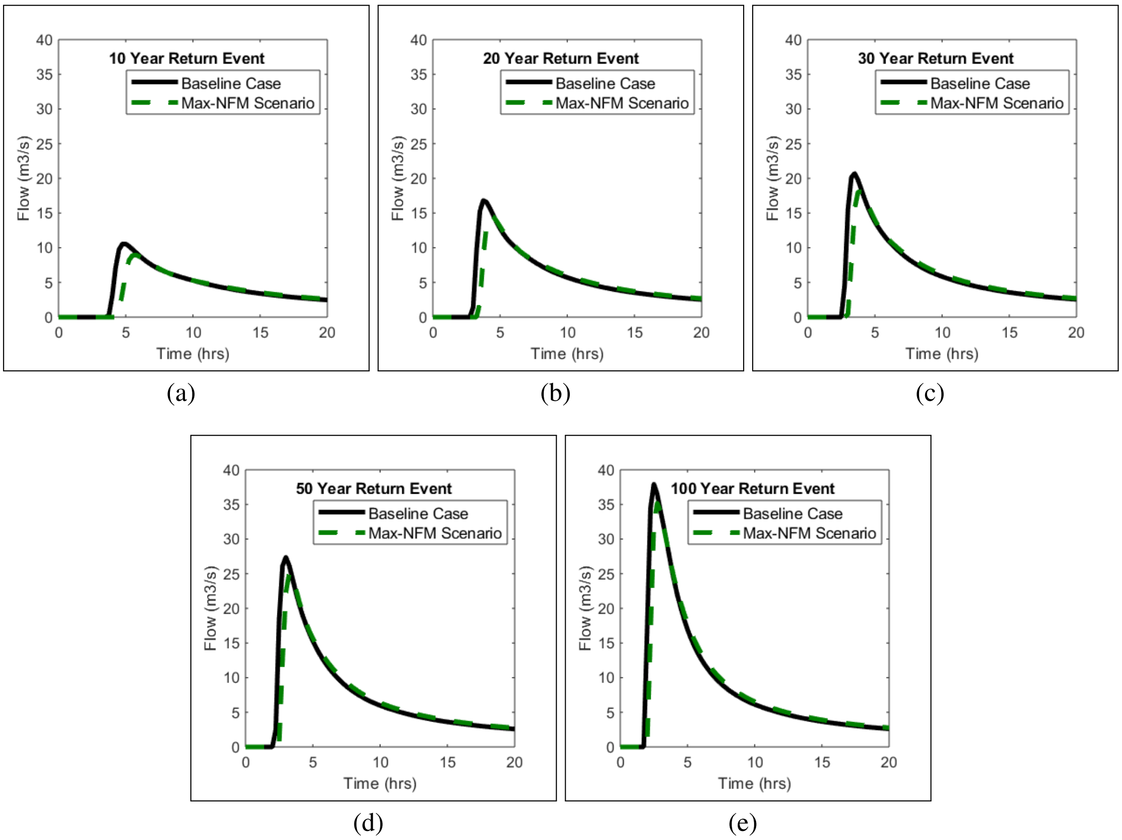
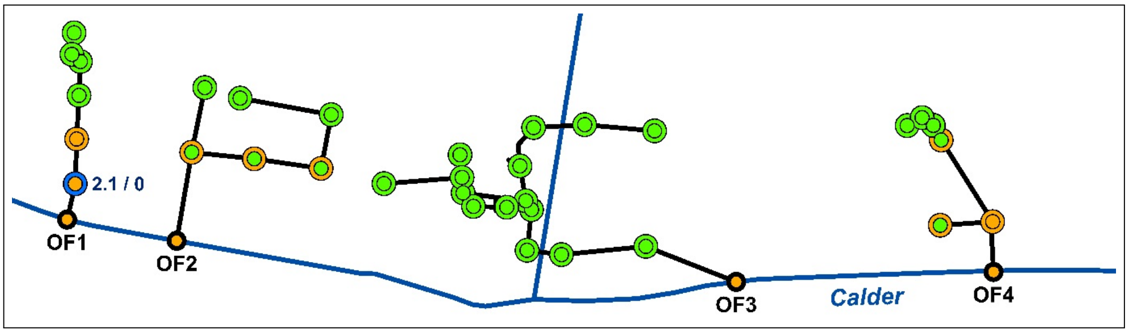


Figure 7.8 Impact of the max-NFM scenario in the Calderdale catchment on a range of design events

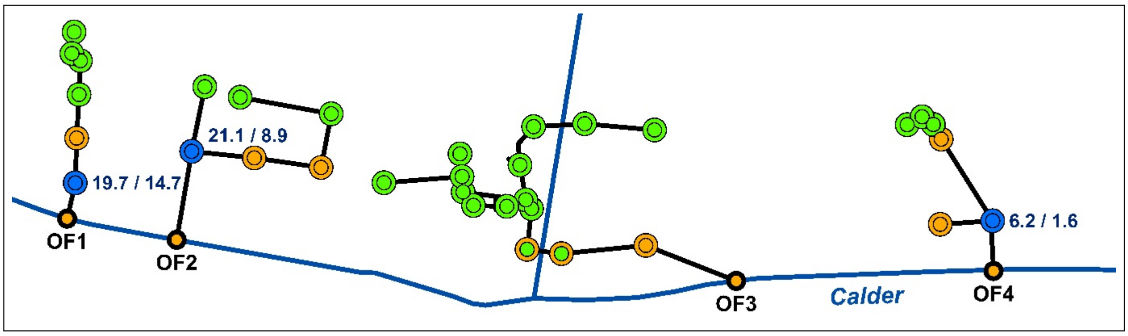
Table 7.3 gives the resultant changes in inundation periods for each of the four outfalls. Again, Outfall 1 is the most susceptible – it is the only one affected by the 10 year event. Outfalls 3 and 4 see inundation during the 20 year event, while the upstream intervention reduces inundation by 0.5 hours for all affected outfalls. The 30 year event has similar effect on the systems, but the greater flows submerge outfalls for longer. Outfall 2 becomes impacted in the 50 year storm, but the diminishing attenuation means the upstream interventions do not significantly reduce the 1.25 hours of inundation.

Table 7.3 Inundation of four different outfalls during base line (B.L.) design events and subsequent NFM-max scenarios (NFM)

	Outfall Inundation periods (hrs)									
	10 Year		20 Year		30 Year		50 Year		100 Year	
	B.L	NFM	B.L	NFM	B.L	NFM	B.L	NFM	B.L	NFM
Outfall 1	0.75	0	2.75	2.25	3.5	3.25	4.5	4.5	5	5.25
Outfall 2	–	–	–	–	–	–	1.25	1	2.25	2
Outfall 3	–	–	2.25	1.75	3.25	2.75	4	4	4.75	4.75
Outfall 4	–	–	1.25	0.75	2.25	1.75	3	2.75	3.75	3.75



(a)



(b)

Figure 7.9 Impact of the max-NFM scenario on Todmorden's surface drainage network during (a) 50 year design event and (b) 100 year design event

Once again, these changes in outfall inundation have varying impacts on the functioning of the contributing sub-systems. The 10 year event does not affect the systems at all (so no perceived benefit from the NFM attenuation). The 20 and 30 year events cause surcharging (but no flooding), with the max-NFM scenario having a mitigating impact. The two largest events do cause flooding (the volumes are shown in Figure 7.9), alongside widespread surcharging. Above Outfall 1 the small amount of surface flooding is completely removed by the interventions (as is surcharging above Outfall 2). The 100 year event causes significant flood volumes in the systems above Outfalls 1, 2 and 4. NFM reduced these volumes by 25%, 68% and 74% respectively. It is also interesting to note that, despite the extension of inundation duration at Outfall 1 during this event, there are still improvements in the performance of the surface drainage (see later Discussion section).

7.4.3 Discussion

The two upstream forms of NFM – implemented simultaneously and at a large scale – have been shown to cause modest attenuation of modelled downstream flows (and hence water levels) within the Calder Valley. As a consequence, there have been alterations (albeit minor) to the performance of the surface drainage network in Todmorden.

Tables 7.2 and 7.3 demonstrate that the inundation of outfalls is dependent on: (i) the magnitude of the rural catchment response and (ii) the section geometry around each outfall. A single event will cause different inundation durations at individual outfalls. Therefore, the attenuation from upstream NFM has varying effects on each. Additionally, the degree of attenuation from NFM is dependent on event severity.

Despite this, the results in Tables 7.2 and 7.3 broadly suggest NFM can reduce inundation for a series of outfalls across a range of events. The greatest reductions occur in the more frequent storms. This is because (i) outfalls are generally submerged for less time and (ii) upstream NFM interventions are having their greatest impact. However, it should be acknowledged that the greatest reductions (which rarely exceed 0.5 hours for any outfall) occur from catchment-scale interventions and often during events when no surface flooding actually occurs (e.g. the 10, 20 and 30 year events).

Table 7.3 demonstrates that the reductions in inundation duration diminish as storm severity increases (to a point where NFM causes no change). Nonetheless, Figure 7.9 indicates continued improvements to performance of the drainage sub-systems. This highlights the effect upstream attenuation is having on the timing of the outfall inundation. By slightly delaying the river's response (illustrated by Figure 7.7), more water is able to escape the urban system before outfall submersion and this increases the effective capacity of the surface network. For instance, the max-NFM scenario does not change the inundation duration of Outfall 1 during the 50 year event, but does delay it by 0.25 hours. This allows $2.1m^3$ more water to escape from the outfall, which means subsequently trapped flow can be contained within the drainage pipes (see Figure 7.9). Interestingly, unlike the varying impacts of inundation duration, the benefit from delaying the rural response applies to all the outfalls for all return periods. The max-NFM scenario has the same effect on the 100 year event (i.e.

delaying the rural response by 0.25 hours), which results in reduced surface flooding across three of the sub-systems (exact volumes are shown in Figure 7.9).

This phenomenon illustrates a mix of consequences in how upstream NFM affects downstream drainage performance. While the impact of NFM on the duration and delay of outfall inundation reduces as storms become more severe, its benefit for surface drainage performance increases. This is because the increase in effective capacity of sub-systems is not utilised in the more frequent storms. Alongside this, differing capacities of sub-systems influence the resultant flooding. For instance, Figure 7.9 shows that during the 50 year event the sub-system above Outfall 3 (which is drowned for 4 hours) is not surcharged and yet, above Outfall 2 (only inundated for 1.25 hours), several manholes are surcharged. The sub-system above Outfall 3 has more capacity through having longer culverts and wider diameters (600mm instead of the 150mm above Outfall 2). As the sub-system is able to contain more surface water, any increase in the effective capacity created by upstream NFM will be less significant. This suggests upstream interventions may have greatest benefit on under-designed systems or those operating at their design capacity.

However, as noted in the first two case studies, storm severity increases, general concerns about fluvial flooding will dominate. During the 100 year event in Todmorden, the Infoworks model indicates there will be out-of-bank flow. Not only would this alter the response of the surface drainage network, it could well eclipse any improvements to outfall inundation.

The importance of outfall inundation timing highlights the assumption of using uniform catchment rainfall in the methodology. The most frequent events (i.e. 10 year and 20 year) pass through the urban surface drainage system before outfalls are inundated. With increased storm severity (and therefore flashier rural response), the tail of the urban response is more likely to be trapped within the surface systems. This would suggest that different storm tracks (which would alter response timings) could significantly change the flooding volumes seen in the urban area – see section 8.3 for further discussion.

Despite being dependent on various factors, it is worth noting that, in all the events examined, upstream interventions have not had any detrimental impact on drainage performance. In most cases marginal improvements have been made, suggesting that 'slowing the flow' broadly has positive repercussions for downstream urban drainage. This could provide further backing to the opportunity-led philosophy of many NFM implementation projects, which often operate under the assumption any upstream intervention will have a net-positive impact.

Admittedly, there are caveats to this finding. By delaying (or indeed prolonging) the inundation period, upstream NFM may be making the drainage system less prepared for future events. A second rainfall event is made more likely to fall on an urban network already containing trapped water (thereby having less effective capacity). Therefore, it could be argued that in such cases the system would be less resilient to rapid multiple events.

7.5 Conclusion

This third case study has built on the previous two to offer further evidence to support the idea that attenuation from upstream NFM (albeit minor) can influence the behaviour of downstream surface drainage. Multiple sub-systems in Todmorden have simultaneously experienced improvements in their ability to discharge freely into the Calder river.

Having evaluated three separate case studies, Chapter 8 will now evaluate two further trends identified in the results. Chapter 9 will then offer a comparative discussion on trends identified across all three modelled catchments.

Chapter 8

Further Studies

8.1 Introduction

The results from the three preceding case study chapters generally suggest that 'slowing the flow' can have a modest benefit for downstream urban drainage systems, although this is dependent on several complex symbiotic factors (a full comparative discussion of catchment results is given in Chapter 9).

The purpose of this chapter is to provide further examination of how NFM could impact downstream surface drainage performance. It does this by conceptualising two distinct forms of variability which could impact the relationship between rural and urban responses.

These two forms of variability, which are dealt with separately, are the roles of: (i) climate change and evolving storm intensities and (ii) the tracking (or direction) of storms moving across the catchment. The primary metric, as throughout this research, is the consequent impact (and potential mitigation from upstream NFM) on outfall inundation periods and surface drainage performance.

Although prompted by the results seen across the three case studies, these two supplemental studies build on the Calderdale catchment's calibrated model (presented in Chapter 7).

The results of the latter half of this chapter (section 8.3) have been presented in Ferguson and Fenner (2020a).

8.2 Influence of Climate Change

Hydrological responses from the UK's rural catchment uplands have evolved significantly since the Second World War (Johnson and Priest, 2008). A primary driver behind this has been the growth of intensive farming practices which are widely accepted to have increased downstream fluvial flood risk (Iacob et al., 2017). Adoption of NFM interventions, by restoring natural hydrological processes, has been viewed as a mechanism with which to combat this trend (Holstead et al., 2017).

However, it has also been suggested that more widespread adoption of NFM practices could be used to alleviate climate-induced stresses (Kay et al., 2019). This is a highly uncertain emerging threat, although there is some agreement over the increasing likelihood of wetter winters and more intense summer storms in the UK and this is expected to exacerbate catchment management issues (Starkey et al., 2017).

8.2.1 Methodology

Section 3.11 laid out the method by which design rainfall events were constructed using FEH catchment descriptors.

The impact of climate change was incorporated using climate scenario factors derived by Dale et al. (2017), which reports on outputs from UKWIR's (UK Water Industry Research) climate-change related research programme. The contained 'uplift factors' are informed by combining two approaches that involve: (1) translating existing rainfall data to areas projected to have similar climates in the future and (2) using a high resolution climate model ($1.5km$ grid size) from the Met Office. These uplift factors have been used elsewhere in the literature, including Pregnolato et al. (2017a) and Kapetas and Fenner (2020). The values used here, which are given in Table 8.1, are those recommended for those within Yorkshire Water's coverage and for storms with an approximate duration of 6 hours.

Table 8.1 Design uplift factors based on different climate scenarios for a 6 hour design storm in the North East England (from Dale et al. (2017))

	Decade		
	2030s	**2050s**	**2080s**
Low Estimate	5%	8%	33%
Central Estimate	7%	17%	51%
High Estimate	10%	30%	75%

The increases given in Table 8.1 were then all applied to the 10, 20 and 30 year design events.

8.2.2 Results

The resultant evolution of baseline catchment responses and max-NFM scenario responses (obtained through the calibrated coupled model described in section 7.3.1) are shown in Figure 8.1 (read down columns for increasing storm intensity and along rows for increasing severity from climate change).

Figure 8.1 gives an indication of how the variance in future storm intensity estimates is translated into small catchment flow response. For instance, the 10 year storm (i.e. top row of Figure 8.1) the percentage difference between the higher and lower scenarios during the 2030s is 15%. This increases to 42% for the 2050s event and 53% for the 2080s.

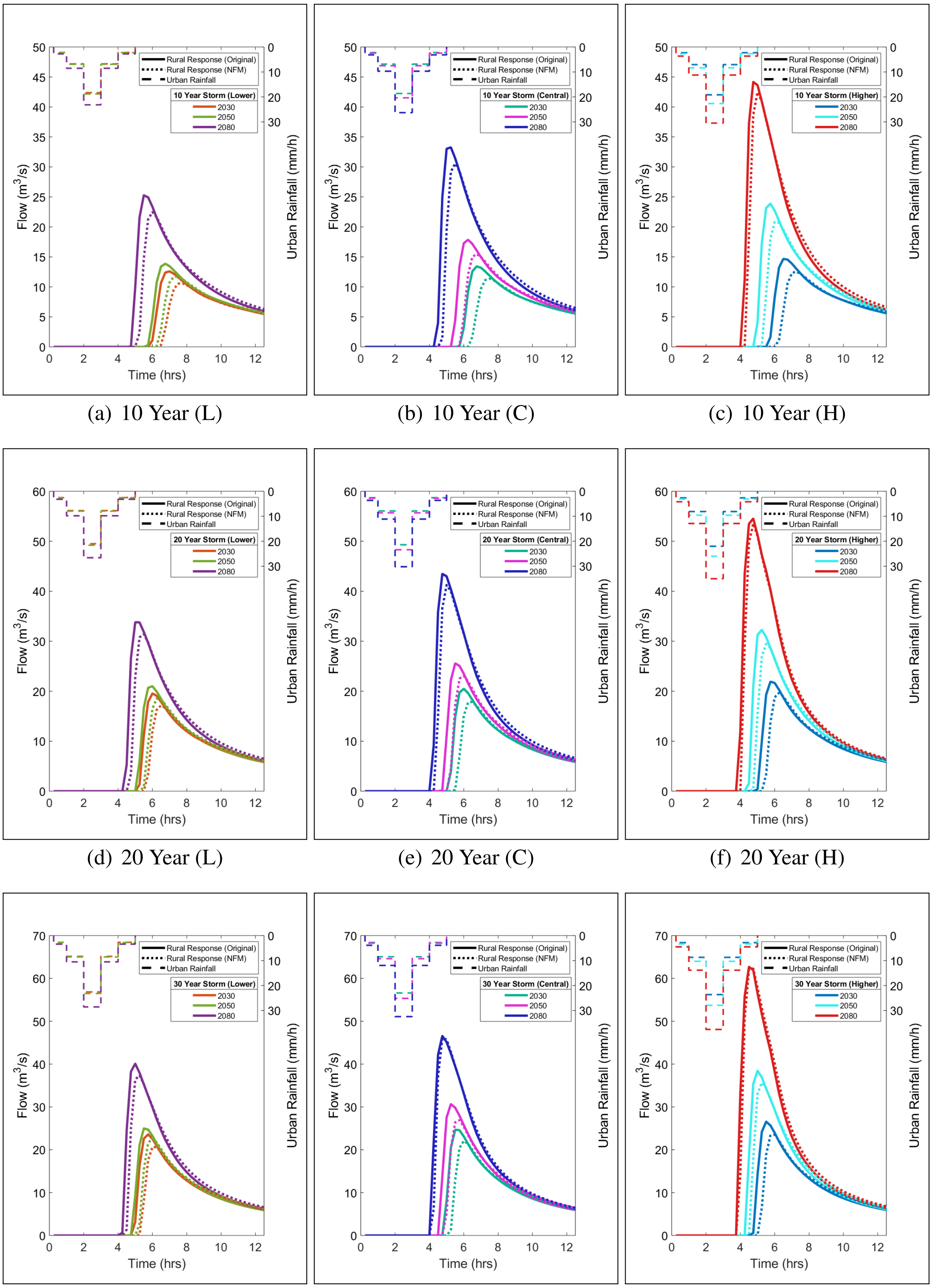
The changes in catchment response have repercussions for the attenuating impact achieved by the max-NFM scenario. Table 8.2 gives both the reduction and delay of the peak magnitude created by the max-NFM scenario for each of the hydrographs given in Figure 8.1.

In essence, NFM impact reduces as storm severity increases - the 10 year event under the lower 2030 scenario is sees a peak magnitude reduction of 16% and is delayed by 0.75 hours. Conversely, the 30 year event under the higher 2080 scenario sees a peak reduction of 0.6% and no delay. This evolution means the max-NFM scenario has greatest impact during the 2030s but, under both the central and higher estimates for climate uplift, the max-NFM scenario would have negligible impact on catchment response for the 2080s during events greater than the 30 year storm. It should be noted that this reflects a static solution (i.e. a constant NFM scenario) against increasing inputs.

These alterations in catchment response have repercussions for the inundation of drainage outfalls. The consequent changes to drainage behaviour were calculated, in the usual way, by applying the output from the rural coupled model as input to the urban drainage model.

Table 8.2 Percentage reduction in peak magnitude of design storms by the NFM-max scenario in the Calder catchment

		Peak Reduction (%)			Time Delay (hrs)		
Return Period		10 Yrs	20 Yrs	30 Yrs	10 Yrs	20 Yrs	30 Yrs
	Low	16	12.3	10.4	0.75	0.5	0.25
2030	Central	15.4	11.7	10	0.75	0.5	0.5
	Higher	14.5	10.3	9.5	0.75	0.5	0.5
	Low	15.5	11.8	9.3	0.5	0.25	0.5
2050	Central	13.3	9.7	8.8	0.5	0.5	0.5
	Higher	12.7	8.7	7.3	0.25	0.25	0.25
	Low	11.1	7.1	6.9	0.5	0.5	0.25
2080	Central	8.1	5.1	1.1	0.25	0.25	0
	Higher	3.8	1.8	0.6	0.25	0	0



(a) 10 Year (L) (b) 10 Year (C) (c) 10 Year (H)

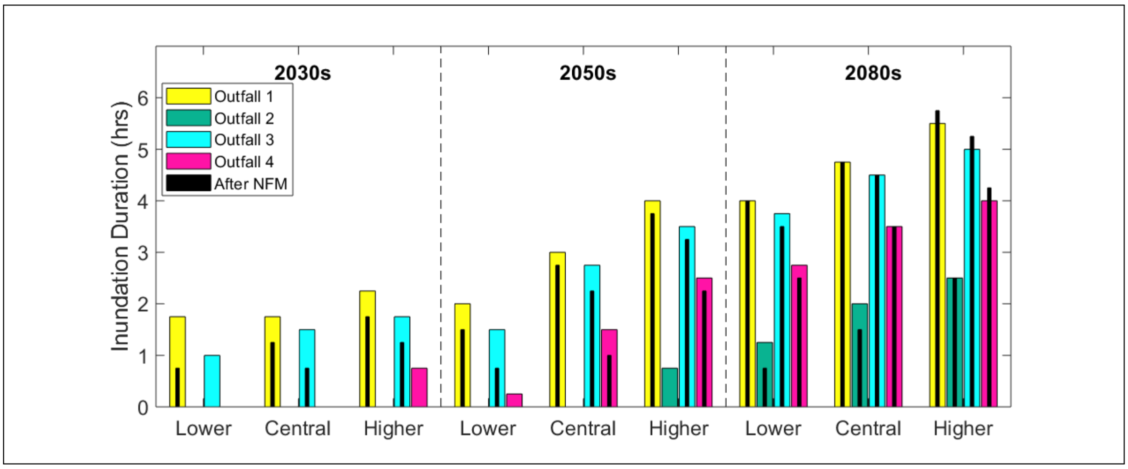
(d) 20 Year (L) (e) 20 Year (C) (f) 20 Year (H)

(g) 30 Year (L) (h) 30 Year (C) (i) 30 Year (H)

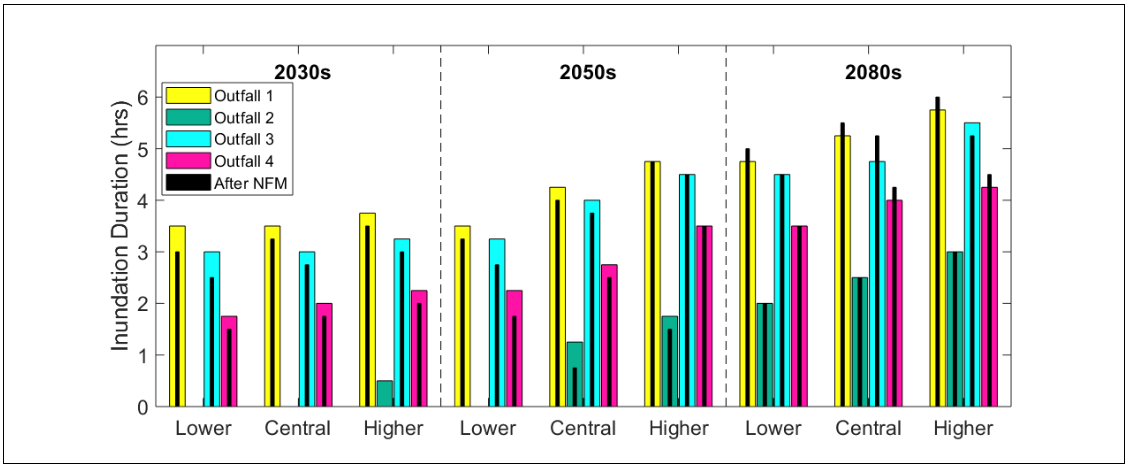
Figure 8.1 Evolution of design storms resulting from climate change factors (given in Table 8.1) and subsequent attenuation from max-NFM scenario

Figure 8.2 gives the inundation durations for each of the downstream outfalls (see Figure 7.1 (b) for Todmorden's drainage layout) for the 10 year and 20 year events under all the uplift factors and epochs.

Figure 8.2 illustrates that there is an increase in inundation duration for all outfalls with the climate-uplifted baseline design storms. Under the central climate estimate, the 10 year storm will cause 3.25 hours of total inundation (i.e. sum of all four outfalls occurring largely simultaneously) in the 2030s and 14 hours in the 2080s. This compares to a rise from 9.5 hours to 16.5 hours (again totals from largely simultaneous inundation) during the 20 year event.



(a)



(b)

Figure 8.2 Evolution of design storms resulting from climate change factors (given in Table 8.1) and subsequent attenuation from max-NFM scenario for (a) the 10 year event and (b) 20 year event

The max-NFM scenario does have some effect on those inundation durations. The greatest reductions are seen during the 2030s. For the lower uplift prediction for this epoch, inundation at Outfalls 1 and 3 is reduced by an hour. However, the event does not cause inundation of Outfalls 2 and 4. In fact, the results suggest that Outfall 2 does not become inundated during the 10 year event until at least the 2050s (although this would be removed by the modelled interventions).

Overall, as the severity of the event increases, the benefit from upstream NFM intervention reduces. However, all outfalls during the 2050s epoch (under all uplift scenarios) experience some form of modest benefit (i.e. a reduction of 0.25 and 0.5 hours). Interestingly however, Outfall 2 sees inundation of 0.75 hours completely removed by the upstream interventions. This is because of the local geometry at the outfall – the baseline event submerges the outfall only briefly and the NFM attenuation reduces the peak flow such that the outfall level is not reached.

There are still marginal benefits from the interventions during the lower and central 2080s uplift predictions. Because of its geometry, Outfall 2 see the greatest reduction (despite not being impacted at all during the 2030 event of same return period). However, during the higher uplift predictions, there begins to be a negative impact from NFM. Similarly to circumstances seen in the earlier case study chapters, the minimal attenuation of large responses slightly extends the inundation of downstream outfalls. This means that, under the higher uplift climate prediction, the max-NFM scenario is actually having a negative impact overall on downstream outfall inundation (because storms are large enough where marginal attenuation is again prolonging inundation periods).

The 20 year event (Figure 8.2 (b)) generally sees smaller reductions in inundation duration across all the 2030s and 2050s potential rainfall uplifts. However, across all three uplift scenarios in the 2080s, the upstream intervention has a negative impact on outfall inundation (for the same reasons discussed above).

As would be expected, these changes in outfall inundation duration make a consequent impact on the performance of the contributing surface systems. Figure 8.3 shows this drainage response under the central climate estimate during the 2030s, 2050s and 2080s epochs for both the 10 year and 20 year events.

The figure shows that the central 10 year event (shown in the left-hand column) evolves from having no impact on drainage performance (in the 2030s) to causing $2.9m^3$ of flood (in the 2080s). This is despite the significant periods of inundation for Outfalls 1 and 3 shown in Figure 8.2. The results suggest that the upstream NFM intervention would continue to have an alleviating impact into the future, reducing the flood volume from the system above Outfall 1 by 79% in the 2080s. This seems to be regardless of the fact Figure 8.2 shows (for

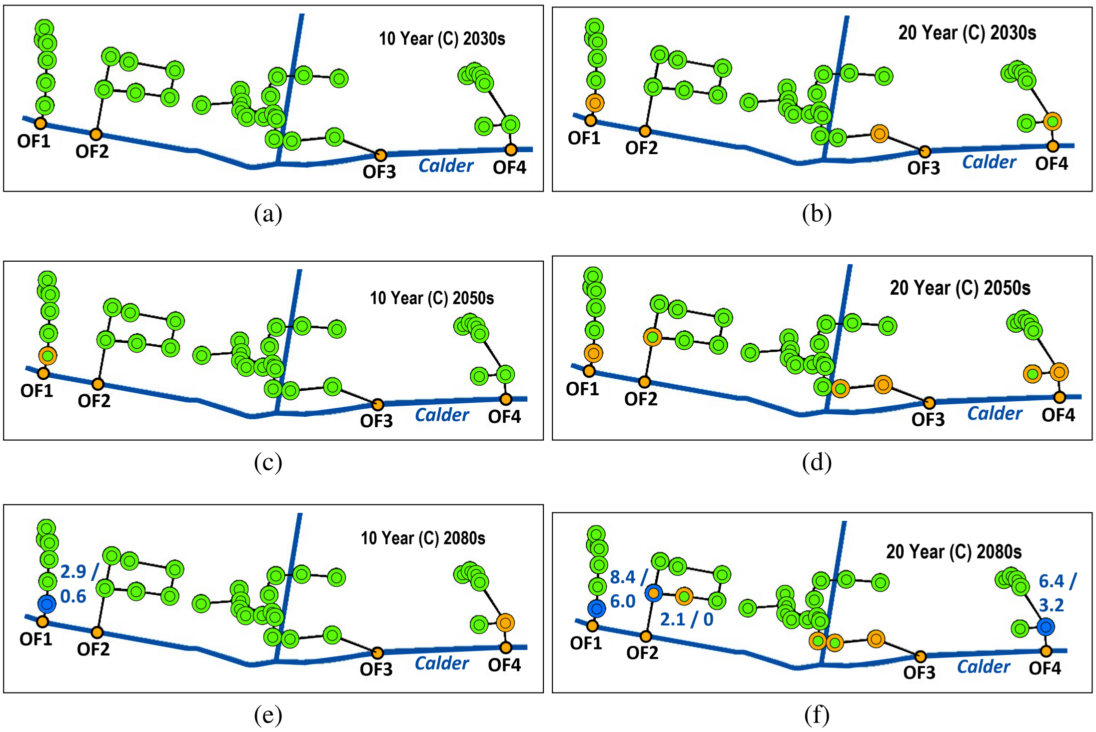


Figure 8.3 Drainage performance in Todmorden during the 10 year and 20 year return periods for the central climate scenario

the same outfall and epoch) no change in the total inundation duration period. The reduction in flooding is explained by the timing of the inundation being slightly delayed (allowing more drainage water to escape through the outfall before submersion). For the same event, the larger capacity of the sub-system feeding Outfall 3 means there is no surface flooding (despite comparable levels of outfall inundation). This is in line with earlier Todmorden results shown in Chapter 7.

The results for the 20 year event are shown in the right hand column of Figure 8.3. During the 2030s and 2050s certain manholes (those closest to the outfalls) experience surcharging. The max-NFM scenario has beneficial impact (although in many cases not sufficient enough to eliminate surcharging). During the 2080s, surcharging leads to flooding above three outfalls (the capacity above Outfall 3 again prevents flooding). The NFM scenario reduces $7.7m^3$ across these sub-systems. Again, these volume reductions occur despite inundation duration increasing at Outfalls 1 and 3 and remaining constant at Outfall 2. The importance of inundation timing is evaluated in the second half of this chapter – section 8.3.

8.2.3 Conclusions

This study has used climate-scaled design storms to examine how evolution in catchment response could affect the attenuating impact of NFM and downstream surface drainage performance.

Outfall inundation durations in Todmorden are likely to increase, with greater intensity of storms also elevating stress on the wider drainage system. The attenuation from NFM interventions diminishes with increasing storm intensity.

The results (which agree with the previous case study work in Chapters 5 and 6) suggest that upstream NFM can continue to have a modest beneficial impact on drainage performance over an extended period of increasing storm intensity.

However, they also indicate that combatting climate evolution with NFM alone is unlikely to be sufficient to compensate for the extra strain on the surface drainage systems caused by additional and more severe storms.

8.3 Variable Rainfall Input under different storm tracks

The results so far have suggested that both inundation duration and inundation timing are critical factors in determining drainage response. Across all three case studies the flashiness of the urban response means the system benefits from both the reduction and delay of the rural hydrograph created by upstream NFM. This is because greater volumes of water are able to escape the drainage system (when compared with the baseline case) before an outfall becomes submerged. This phenomenon could also be viewed as the upstream interventions modestly improving drainage performance by *desynchronising* the rural and urban response. This desynchronisation idea (i.e. of outfall inundation timing) will be the focus of the remainder of this chapter which, similarly to section 8.2, builds from the case study given in Chapter 7.

In considering the synchronisation of rural response and urban rainfall, the timing of the urban rainfall becomes critical. So far, this research has assumed uniform rainfall across the whole catchment (i.e. rainfall falling in both urban and rural environments simultaneously). However, the research in this section evaluates NFM's impact on downstream drainage performance under different storm tracks.

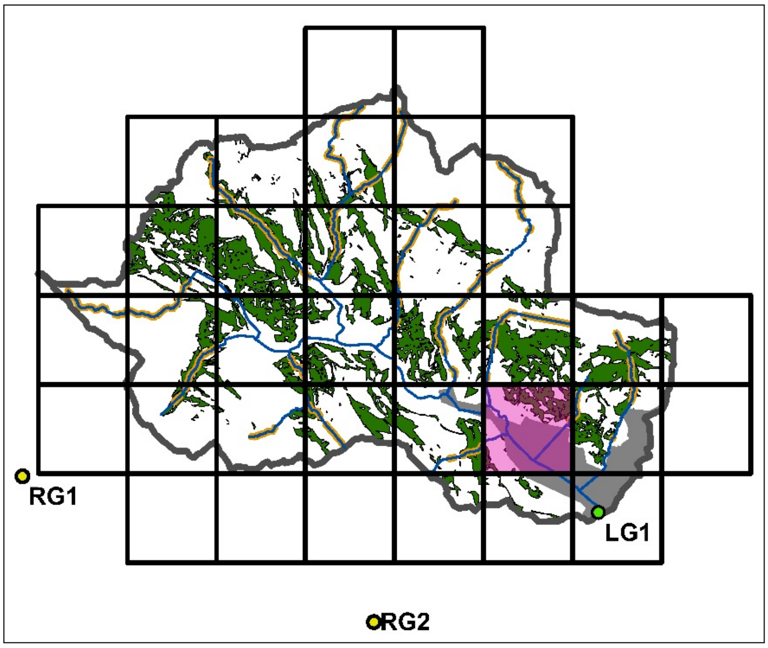
8.3.1 Methodology

Studies have shown that spatial variation in rainfall across catchments can influence downstream response both to a significant extent (Zoccatelli et al., 2010) and to a lesser degree (Adams et al., 2012; Tarolli et al., 2013). It has been suggested that influence is dependent on the scale of the catchment and rainfall event (Nikolopoulos et al., 2014; Weijian et al., 2015). At hill slope and small catchment scale, with less dampening of the hydrological response, other studies have highlighted the potential influence of spatially-varying rainfall (Faurès et al., 1995; Gires et al., 2012; Terink et al., 2018).

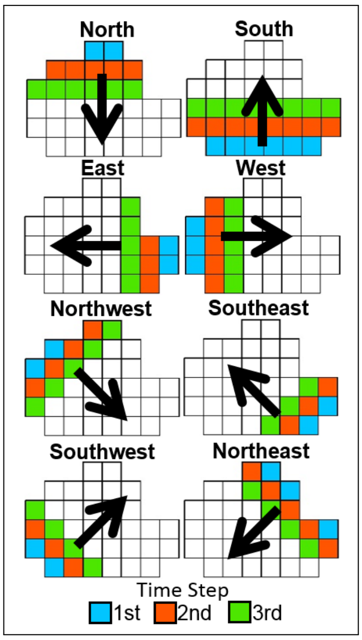
It was hypothesised that the flashy response from the small case study catchment could be influenced by different storm tracks. After the calibration (shown in Figure 7.5), five different design events (10, 20, 30, 50 and 100 year return periods) were run through the calibrated model. Each design event was applied with eight different storm directions (shown in Figure 8.4 (b)) with extents spanning the whole watershed. The variable rainfall was applied using a simple grid square method, with a resolution of $1km$. The squares (incorporated into the original Dynamic TOPMODEL discretisation) each received an individual rainfall input. The movement of the design events (each five hours long) was represented by lagging the storm profile for different squares in such a way the storm front moved from square to square with the model's 15 minute time step. This roughly equates to a storm speed of $1.1m/s$. Marshall

(1980) suggests this is roughly as low as could be expected in the UK. Other models have used comparable speeds when evaluating variable rainfall (De Lima and Singh, 2002; Watts and Calver, 1991). This is, however, a critical methodological assumption for which the repercussions are discussed further in section 8.3.2. For every storm direction, each grid square sees the same profile (albeit at different times), meaning the total volume of water entering the catchment remains constant. Across the eight storm directions, the rainfall input for the urban drainage model is the profile of the highlighted grid square in Figure 8.4 (a).

It is acknowledged that this is a highly idealised representation of spatially-varying design rainfall. It does not allow for factors including: (i) different (and varying) storm track velocities (discussed in Nikolopoulos et al. (2014)) (ii) non-linear storm tracks (iii) different (and varying) storm extents and (iv) topographical influences (discussed in Buytaert et al. (2006)). Given these numerous potential degrees of freedom (and given the small catchment area), using a storm extent spanning the catchment length and travelling at a constant speed was deemed suitable for the scope of this study. However, it is recognised that different grids (in both resolution and positioning), different storm profiles and faster storm fronts will alter how the catchment responds and may affect the response of downstream drainage to outfall inundation. This could be an area for further study and refinement.



(a)



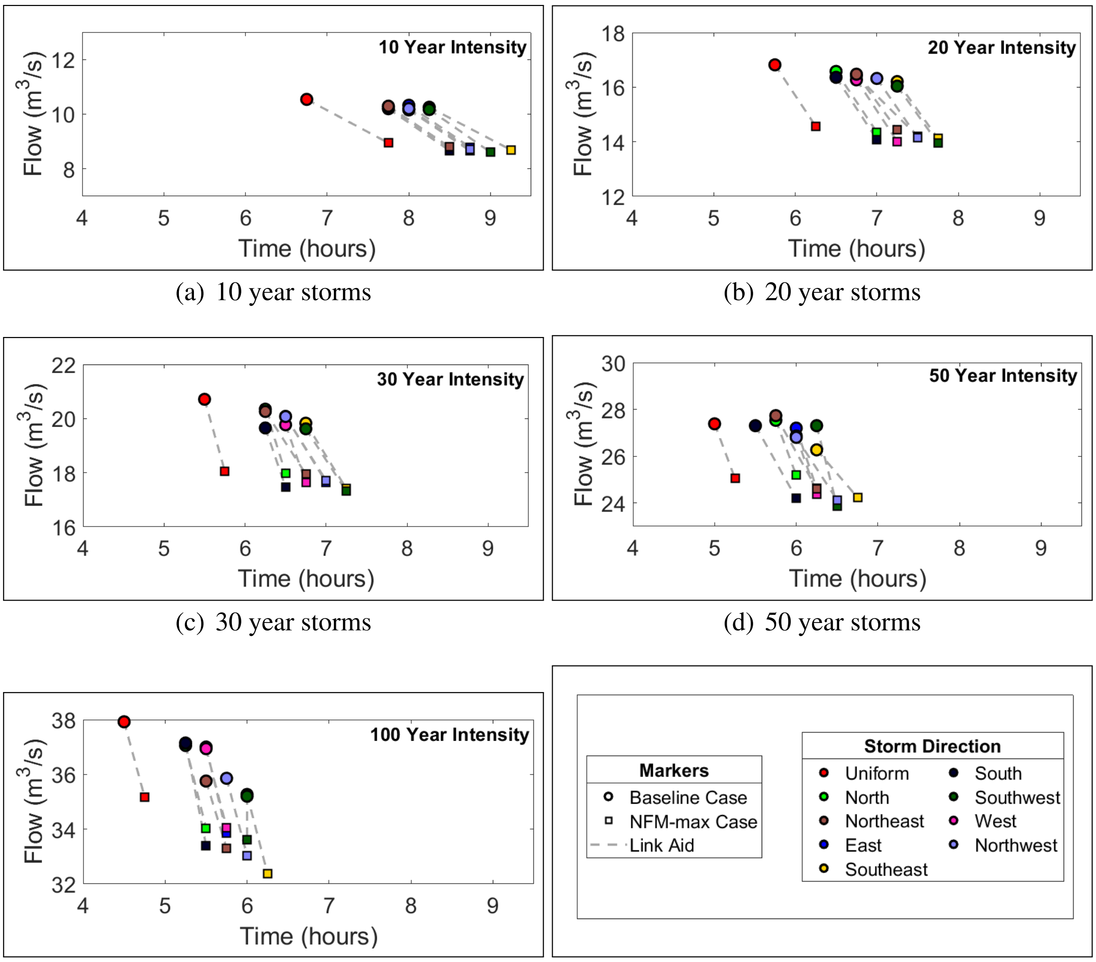
(b)

Figure 8.4 (a) Map of the Upper Calderdale catchment (with locations of NFM intervention as shown in Figure 7.1) and overlying grid (with $1km$ resolution) used to apply variable rainfall and (b) Representation of variable rainfall direction (first three time steps)

8.3.2 Results

After calibration, the five design events (each with eight different storm directions) were run through the coupled model. These are referred to as the 'baseline' cases. The same cases were then run through the coupled model with the the subsequent NFM-max scenario. Figure 8.5 shows the resultant peak magnitudes and timings (for all directions and both the baseline and max-NFM scenarios).

As the catchment drains towards the southeast, a storm from this direction might have been assumed to produce the quickest response. However, the southeast and southwest directions produced the latest peak across all five storm intensities. In fact, the south storm consistently generated the earliest peak (arriving up to 0.75 hours earlier). Figure 8.4 (b)



(a) 10 year storms

(b) 20 year storms

(c) 30 year storms

(d) 50 year storms

(e) 100 year storms

(f) Key

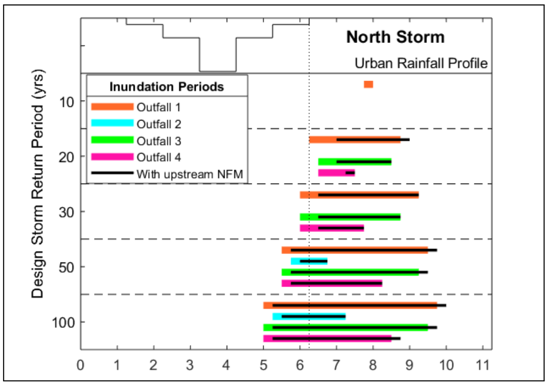
Figure 8.5 Comparison of peak magnitudes from the Calder catchment across variable storm directions under both baseline and NFM-max scenarios for five different design intensities shows that during the southeast event, eight grid squares are receiving rainfall after three time steps – this compares with the south event which is engaging 22 squares within the same period. This would suggest that the catchment shape is a dominant factor in determining concentration time, as this dictates how much water enters the catchment in the early time steps.

Figure 8.5 also shows that the variation in peak magnitude across different storm directions is not consistent through different storm intensities (e.g. the northeast storm does not consistently produce the highest peak magnitude). This variation, although not significant, grows with the increase in storm intensity – the 10 year peaks are all within 1.7% of each other, while for the 100 year event this range increases to 5.3%. This variation could result from the increased intensity of rainfall making the downstream hydrograph more contingent on spatial and temporal variations in sub-catchment response.

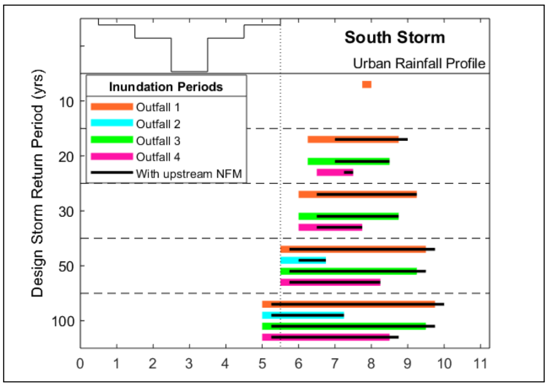
As would be expected (given the results presented in Chapter 7), the attenuation from NFM is modest – especially given the scale of the upstream intervention. However, these attenuations in flow have translated to changes in the water level regime at each of the four downstream urban outfalls. Figure 8.6 compares these periods of outfall inundation (for both the baseline case and the upstream NFM scenario) with the urban rainfall profile for each of the different storm directions.

The first thing to note is that only Outfall 1 was inundated by the baseline 10 year storms. This was just for a short period – a maximum of 0.5 hours – which is subsequently removed in the NFM scenario. During the 20 year events, inundation occurs earlier and is more significant. Across all directions, Outfall 1 is submerged for the longest period (up to 2.75 hours), but Outfalls 3 and 4 also become inundated by the higher flows. The attenuation from upstream NFM is no longer sufficient to remove inundation in any storm direction, but does both delay and reduce these periods. Interestingly, for the 20 year events, Outfall 3 sees the greatest improvements (despite not being inundated at all during the 10 year event). This is because the peak reduction from upstream NFM, although modest (average of 13.3% across all storm directions), is sufficient to significantly reduce the time that the water levels are above the outfall (by up to 75%). Complex inter-dependencies between event magnitude and outfall section geometry determine upstream NFM's ability to influence inundation durations.

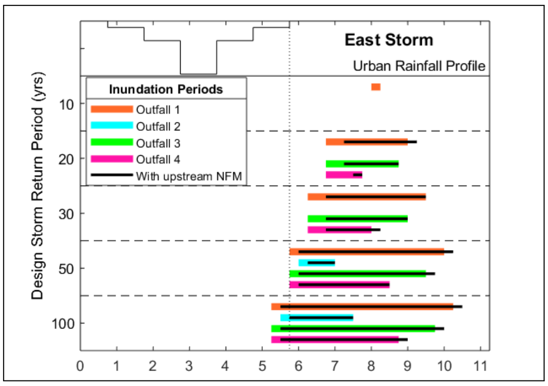
As storm severity increases to 30 year events, inundation periods increase still further and certain storm tracks (north, northwest and west) result in cases of rainfall falling on the urban environment while outfalls are submerged. The attenuation from the upstream NFM scenario means that this submersion is then avoided during the north and west directions. However, with the reduced attenuation of the hydrograph, outfalls do remain submerged for



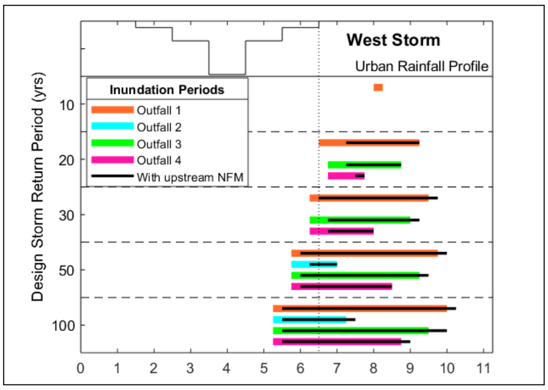
(a) North direction



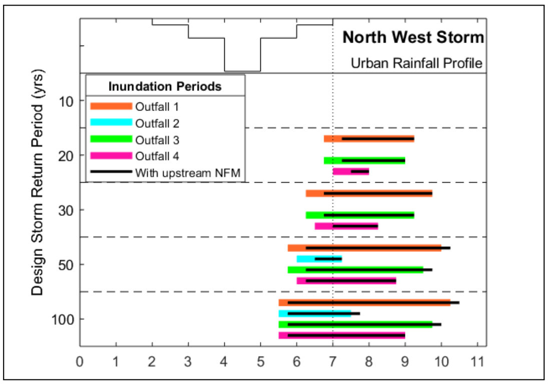
(b) South direction



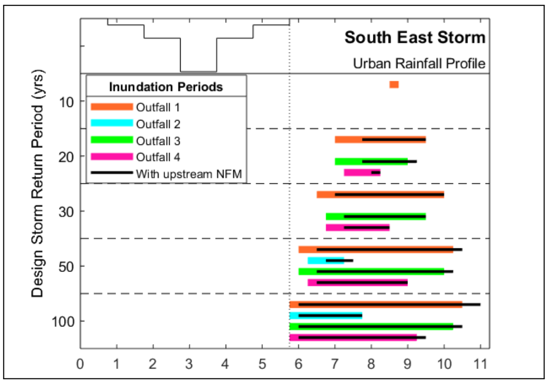
(c) East direction



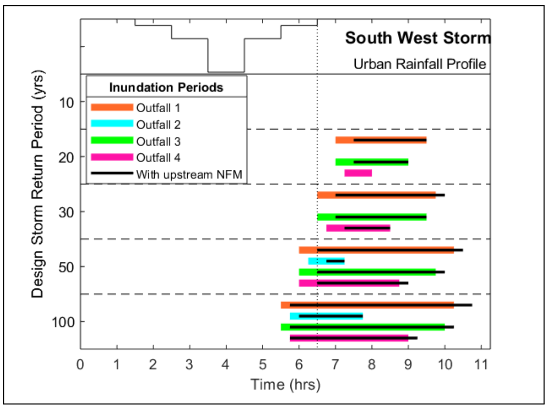
(d) West direction



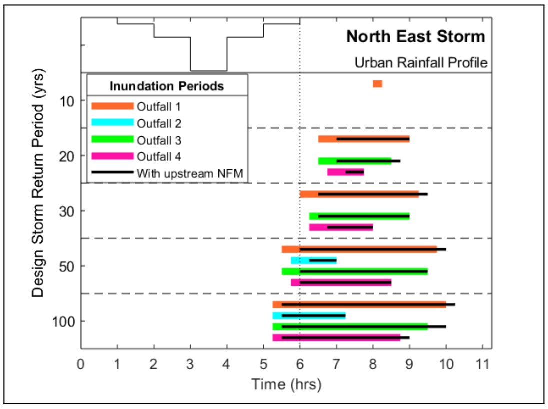
(e) North West direction



(f) South East direction



(g) South West direction



(h) North East direction

Figure 8.6 Inundation of four Todmorden outfalls (and corresponding urban rainfall) for eight different storm directions extended periods of time – a minimum of 3.25, 2.75 and 1.75 hours – at Outfalls 1, 3 and 4 respectively.

Water levels during the 50 year event are sufficient to inundate Outfall 2. The geometry of the outfall sections means that, despite peak magnitudes only being reduced by an average of 10.0%, the inundation period of this outfall is reduced by up to 50% (southwest direction). However, the same event severity inundates Outfall 1 for a minimum of 4 hours (and the NFM scenario only reduces this by 0.25 hours).

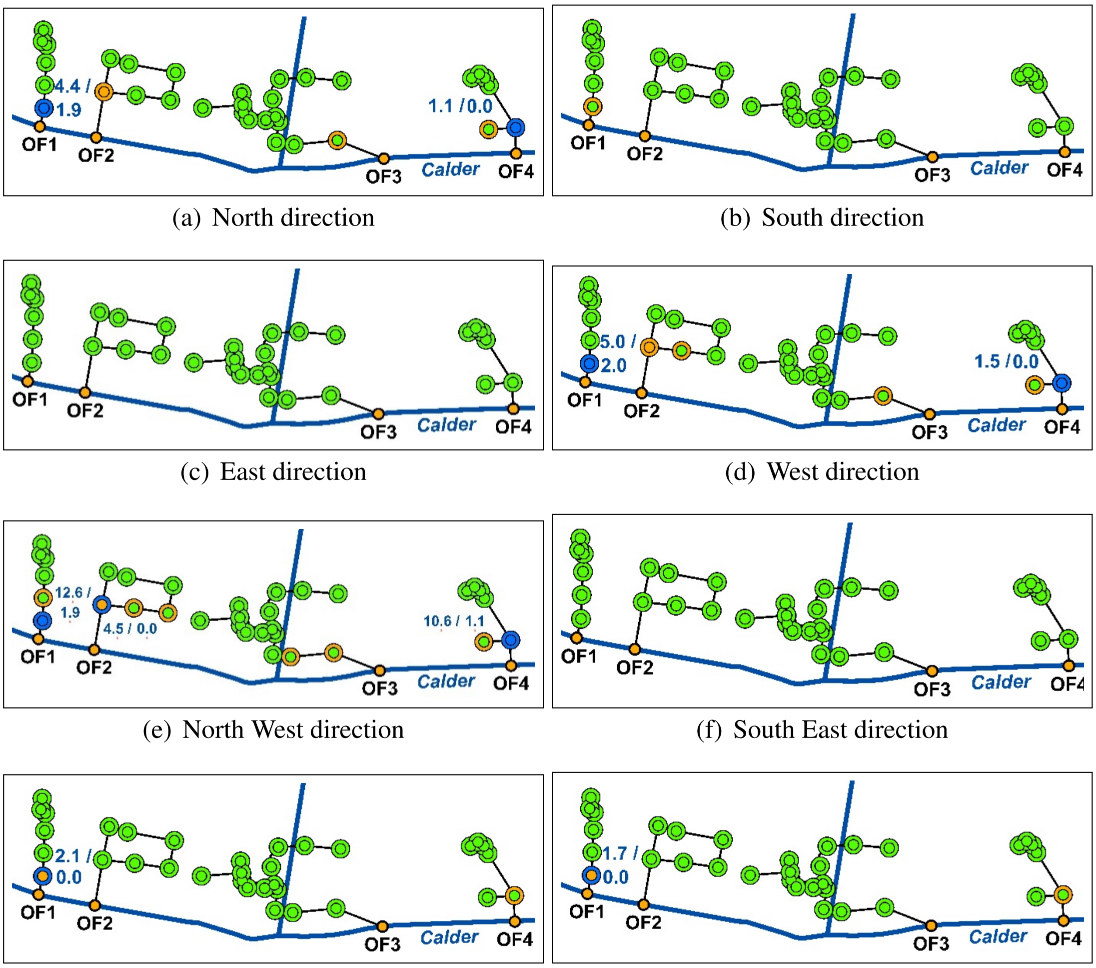
The 100 year event causes the earliest and longest inundation periods. The flashiness of the response also means that outfalls all become submerged at the same time. The slight attenuation from the NFM scenario for the 100 year events typically delays inundation by 0.25 hours.

Figure 8.7 shows how the alterations in outfall inundation translate into changes in the performance of the wider drainage system. The figure concentrates on the eight different storm directions for the 50 year event.

The baseline events for the south, southeast and east directions cause no surcharging or flooding of any of the four sub-systems. Any subsequent NFM therefore has no effect on drainage performance. Figure 8.6 shows that these are the three events when the rural response inundates outfalls after the urban rainfall has occurred. As the storm direction moves away from the southeast quadrant, the baseline case has an increasingly detrimental impact on the drainage performance. The worst case is the northwest storm direction when outfall inundation causes $12.6m^3$, $4.5m^3$ and $10.6m^3$ of flooding from the systems above Outfalls 1, 2 and 4. However, delaying the rural response through the NFM scenario reduces these volumes by 85%, 100% and 90% respectively.

Despite the inundation of outfalls during the 10 and 20 year storms, none of the storm directions cause either surcharging or flooding of the urban system. The northwest storm direction creates the worst performing drainage for both the 30 and 100 year events (although in the former there is only $1.8m^3$ of flooding from the system above Outfall 1 which is then removed under the NFM scenario). In the 100 year event the flood volumes from the baseline northwest across all sub-systems are significant – $25.6m^3$, $9.8m^3$, $89.5m^3$ and $31.6m^3$ from the systems above Outfalls 1, 2, 3 and 4 respectively. This compares with the southeast event which, while causing surcharging, causes no surface flooding.

Figure 8.6 demonstrates that the majority of urban rainfall occurs before the rural response passes through the receiving watercourse. Despite this, the results suggest that the resultant performance of Todmorden's surface drainage system is influenced by the degree of synchronisation between urban rainfall and heightened levels in the receiving watercourse. This varies according to several factors. The first is storm track. Storms from the north and



(a) North direction (b) South direction

(c) East direction (d) West direction

(e) North West direction (f) South East direction

(g) South West direction (h) North East direction

Figure 8.7 Alterations in Todmorden's drainage performance (resulting from outfall inundation) during the 50 year event intensity under eight different storm directions

west lead to synchronisation of urban rainfall and outfall inundation, which hinders drainage performance. Conversely, south and east storms result in the urban rainfall passing through the drainage system before outfalls are impeded. The prevailing storm direction in the Calder Valley is the south west direction. The second factor is storm intensity. Figure 8.6 shows that as storm intensity increases outfalls become submerged earlier. The resultant deterioration in drainage performance is compounded by the increased rainfall. Thirdly, the local geometry around each outfall plays a role. Lower ones are submerged earlier, increasing the probability of synchronisation between outfall inundation and urban rainfall. The influence of this factor (which is discussed in Chapter 7) diminishes with increased storm severity because the flashier response drowns different outfalls simultaneously.

Generally, by 'slowing the flow', the upstream NFM scenario improves drainage performance by de-synchronising urban rainfall and outfall inundation. NFM's ability to do this varies with storm direction and storm intensity. As noted earlier, under certain storm tracks there is no outfall inundation, meaning that any impact from NFM on drainage performance is negligible. The same is true for frequent storms – despite interventions having their greatest flow attenuation. As storm severity increases, despite the diminished impact, NFM interventions are able to allow more water to escape from the surface drainage outfalls (under certain storm directions). This results in significant reductions in surface flood volume for very intense events.

With these larger events comes increased risk of fluvial flooding. The Infoworks model suggested there would be out-of-bank flow in Todmorden (with and without the upstream NFM intervention) during all of the 100 year storm directions. This would overwhelm any impact from NFM on surface drainage performance.

It is worth noting that during no storm tracks has the upstream intervention had a detrimental impact by synchronising outfall inundation with urban rainfall. There are three cases when the slight attenuation of the 100 year event has prolonged the time an outfall is submerged (see Figure 8.6), but the small delay in inundation improves performance of the network in responding to the single event. However, this highlights the limitation of modelling the design storms with a single 'pulse' of rainfall. Although NFM has been successful in de-synchronizing a single event, the delay in outfall inundation may make the urban drainage system more vulnerable to further rainfall. Temporal patterns in urban rainfall could be an area of further study.

8.3.3 Conclusions

The results of this study on spatially-varying rainfall suggest that differing storm tracks across the Calder valley impacts the inundation of Todmorden's surface drainage outfalls. In the most frequent events, the rural response (resulting from any storm direction) is insufficient to drown outfalls for a prolonged period, thus drainage systems are able to continue discharging freely. As storm severity increases, extended periods of outfall inundation become more synchronised with urban rainfall and the role of the storm track becomes more acute. The resultant drainage performance during different 50 year events can vary between causing $26m^3$ of surface flooding (northwest direction) and having no detrimental impact at all (southeast).

As was the case for previous results using uniform response, the rural response is consistently slower and it only ever drowns outfalls during the latter stages of the urban rainfall. Therefore, 'slowing the flow' causes desynchronisation of the two responses and modest benefit for drainage performance. Benefit from the upstream NFM is greatest in the most adverse storm directions, which in this case is the northwest direction – reducing flood volumes by approximately $24m^3$ during the 50 year event. However, in more intense events, fluvial flooding will become the dominant mechanism (as discussed in section 9.4).

Interestingly, the results of this section potentially suggest that broad watershed characteristics (i.e. the location of the urban environment with respect to the wider rural response and the prevailing weather direction) could be used to identify catchments where NFM would have greatest success in de-synchronising rural and urban responses (see section 9.7 for further discussion on this).

It should also be noted that there are other forms of variability such as urban growth or storm patterning (discussed further in section 9.7) which would also influence the impact of NFM across the rural-urban interface.

Chapter 9

Discussion

9.1 Introduction

This chapter begins by identifying similar trends across the results from the three case studies (Chapters 5 to 8). In sections 9.2 and 9.3 the focus is on the benefits accrued by the downstream drainage through evaluation of (i) changes in outfall inundation and (ii) consequent alterations in system performance. Section 9.4 switches the discussion to evaluate how improving drainage performance could be beneficial for arguments supporting upstream NFM. Section 9.5.2 offers explicit recommendations for each of the case study catchment before finishing by discussing how the identified trends could be applicable for flood risk practitioners.

Following this, there is reflection on the coupled methodology and key sources of uncertainty which may influence the identified trends. The chapter finishes with three detailed discussions on avenues for potentially valuable further work.

The subsequent concluding Chapter 10 will respond directly to the central research question and supporting sub-questions put forward in section 1.2.

9.2 Impact of NFM on outfall inundation

The terms 'inundation threshold' and 'inundation duration' in relation to how urban watercourses can impact drainage outfalls were explained in section 2.3.1 and illustrated in Figure 2.6.

The results across all three case studies indicate that upstream NFM can have an impact on the time a surface drainage outfall is submerged by the downstream watercourse during storm events (i.e. the inundation duration). Figures 5.5, 6.6 (a) and 8.2 all suggested that upstream interventions can both reduce and increase the time outfalls are submerged – the trends behind this will now be discussed.

Figure 9.1 (a) shows how the upstream max-NFM scenario changes the inundation duration at all outfalls evaluated across the three case studies (during a range of design events).

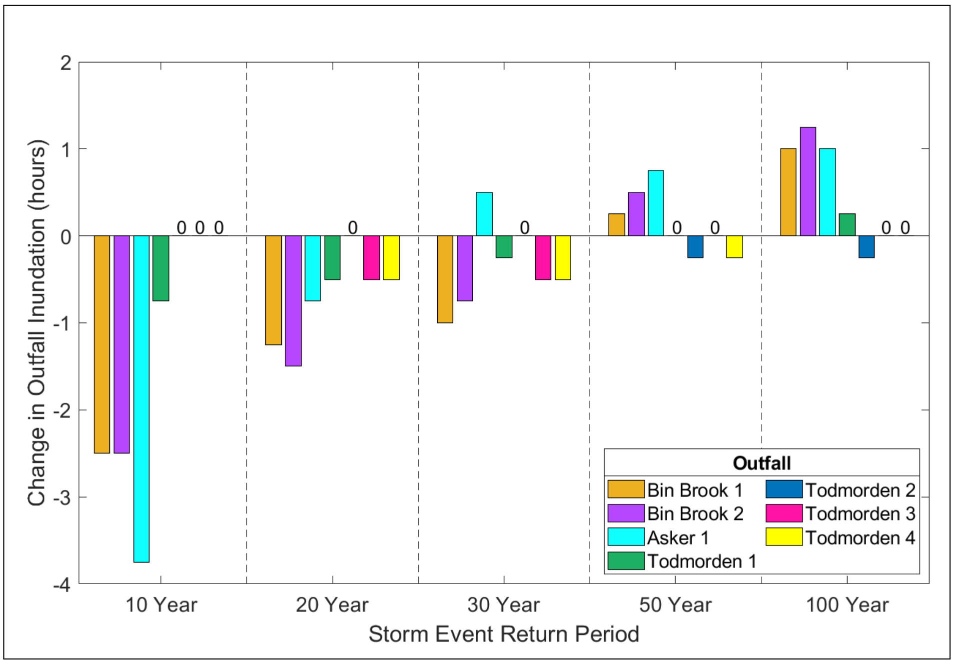
The figure shows that, for all outfalls, the greatest reductions in inundation duration are seen for the most frequent event (10 year). The differing inundation thresholds (specific to each outfall) mean these benefits vary. In the Asker catchment all 3.75 hours of baseline inundation are removed by NFM, whereas Outfalls 2, 3 and 4 in Todmorden see no inundation during the equivalent baseline event.

As storm severity increases, the inundation duration reductions generally diminish. Across all three case study catchments NFM-induced water level attenuation reduces with increased storm intensity (see Figure 9.3). Despite this, the slight attenuation during larger events begins to cause extensions of the inundation duration (this behaviour has been identified through the results chapters). Of the seven outfalls evaluated in this research, this phenomenon occurs at four during the 100 year event.

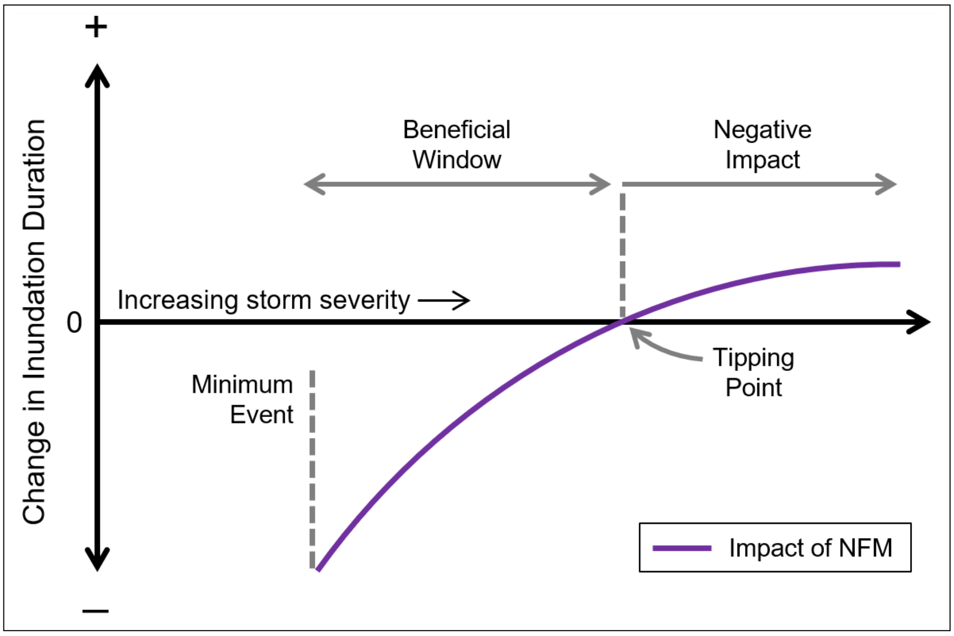
Given the trends seen in Figure 9.1 (a), which extend across multiple outfalls in different catchments, the results *suggest* a generalised relationship between upstream natural interventions and changes in inundation durations at downstream outfalls (while in absolute terms being greatly influenced by specific local geometry).

Figure 9.1 (b) attempts to describe this relationship generally for a single outfall across a range of event severities.

To begin with, there is a minimum event severity when the inundation threshold is breached by the receiving watercourse (i.e. outfall submersion occurs) and upstream attenuation can have benefit. The results in Figure 9.1 (a) suggest that this threshold is highest for Todmorden's Outfall 2 (because we see no benefit until the 50 year event). At first Figure 9.1 (a) appears to indicate the Asker outfall has the lowest minimum event threshold (because it has greatest benefits during the 10 year event). However, the inundation threshold for this outfall is such that water levels only just submerge the outfall (for 3.75 hours). This means the modest attenuation from upstream NFM is of great benefit to the outfall inundation metric. In fact, the Bin Brook outfalls are submerged for at least 8.75 hours during the 10 year event. This longer baseline inundation limits the degree to which attenuation (from NFM upstream) can produce large reductions. Nonetheless, the beneficial impact of NFM on inundation duration is greatest just after the inundation duration is breached. As storm severity increases, outfalls are submerged for longer and any alleviation from upstream interventions diminishes.



(a)



(b)

Figure 9.1 (a) Changes in outfall inundation duration resulting from the upstream max-NFM scenario over five different design storms in all three case studies (b) a conceptualised relationship of NFM impact on downstream inundation duration

The results presented in Figure 9.1 (a) reinforce previous observation that, as storm intensities increase, there is a reversal in how attenuation from upstream interventions changes the inundation duration. For the relationship shown in Figure 9.1 (b), the storm frequency at which this occurs has been termed the 'tipping point'.

This would then indicate that there is a 'window' of storm intensities within which NFM has a beneficial impact on downstream inundation durations. This window is outfall specific and is dependent on the scale of the upstream intervention. The lower the inundation threshold, the more frequently interventions are effecting downstream watercourses within this beneficial window. This would suggest that upstream NFM is most effective in catchments where outfalls are frequently submerged. On the other hand, such outfalls also appear to reach the tipping point (induced by upstream interventions) in more frequent storms. Those outfalls that are higher above the invert of the urban watercourse (that see no benefit in frequent storms) continue to see reductions in more severe events (e.g. Outfall 2 in Todmorden). However, it should again be acknowledged that fluvial flooding will then become increasingly dominant. For instance, the Todmorden Infoworks model suggests fluvial flooding across all four drainage areas (see Figure 7.1 (a)) during the 100 year event and, in such circumstances, any slight change in outfall inundation duration would likely be redundant.

The non-linear form of the relationship shown in Figure 9.1 (b) is informed by at least two factors. Firstly, as storm severity increases, the impact of any particular NFM intervention will reduce (Dadson et al., 2017). This will diminish the impact of that intervention on the duration of inundation. Secondly, in typical river morphologies, as flows increase significantly so does the cross-sectional area of the flow (thereby radically altering the depth-flow relationship). In such circumstances, NFM's attenuation of flow volumes will have less effect on water depth, meaning reduced impact on the submerged outfall.

There are several additional points to note about the conceptual relationship presented in Figure 9.1 (b). Firstly, tipping points are not necessarily linked to definitive storm intensities. Outfall 3 in Todmorden sees zero effect on the inundation period during both the 50 year and 100 year events. This reflects a combination of local geometry at that outfall and the minimal impact of upstream NFM in severe events.

Secondly, this relationship has been derived with highly idealised design storms, which are essentially a single, uniform pulse of rainfall resulting in downstream outfall inundation (see section 3.11 for discussion on design storm construction). Different rural hyetographs will alter how the downstream response submerges outfalls, potentially leading to extended periods of inundation (this has been seen in several of the case study calibration events). This would alter both (i) the attenuation achieved by any upstream intervention and (ii) how any attenuation would alter the downstream water level regime in the urban watercourse. Section

9.7 gives more detailed discussion on the potential for storm patterning to alter the effects of inundation periods.

Thirdly, the relationship presented in Figure 9.1 (b) is for a single (large scale) intervention. Different levels of attenuation will result in alterations in the relationship. Smaller interventions will have a smaller impact on inundation durations but are therefore less likely to have a detrimental impact in the more intense events. It should also be noted that the impact of intervention failure (i.e. a cascade of failing woody debris dams) is more likely to occur in the most intense events, reducing any detrimental attenuating impact they might have (although there could be other consequences such as culvert or bridge blocking).

Overall then, the relationship between upstream NFM attenuation and outfall inundation is complex. However, there appear to be some common trends running through the results – NFM attenuation causes greatest duration reductions when flows first rise above the inundation threshold, these diminish with increased storm severity and the same interventions can also cause prolongation of inundation for the most susceptible outfalls in larger events. Section 9.5.2 discusses how these identified trends may be of wider use to practitioners looking to develop a 'risk profile' for a particular outfall being inundated by a local watercourse, along with an understanding of how attenuation from upstream NFM could contribute to alleviating this phenomenon.

9.3 Impact of NFM on drainage performance

Section 9.2 evaluated how upstream NFM interventions influence the inundation duration of outfalls. However, the results across all three case studies suggest that the *delay* of inundation translates into significant improvements to drainage performance. This section will aim to better understand this metric of 'slowing the flow' in achieving benefits for downstream surface drainage.

Figure 9.2 (a) compares the change in outfall inundation duration (resulting from upstream max-NFM scenario) against the consequent reduction in flood volume discharged from the contributing drainage system. The figure does this for five uniform design events (10, 20, 30, 50 and 100 years) in each of the three case study catchments. Figure 9.2 (b) does the same thing, but compares the surface flooding reduction with the inundation delay induced by the upstream interventions. At no point were the flood volumes increased as a result of the upstream NFM.

The instances where outfall inundation did not occur (e.g. Todmorden outfall 2 during the 10, 20 and 30 year events) are not shown on the plot. Neither are the two cases when

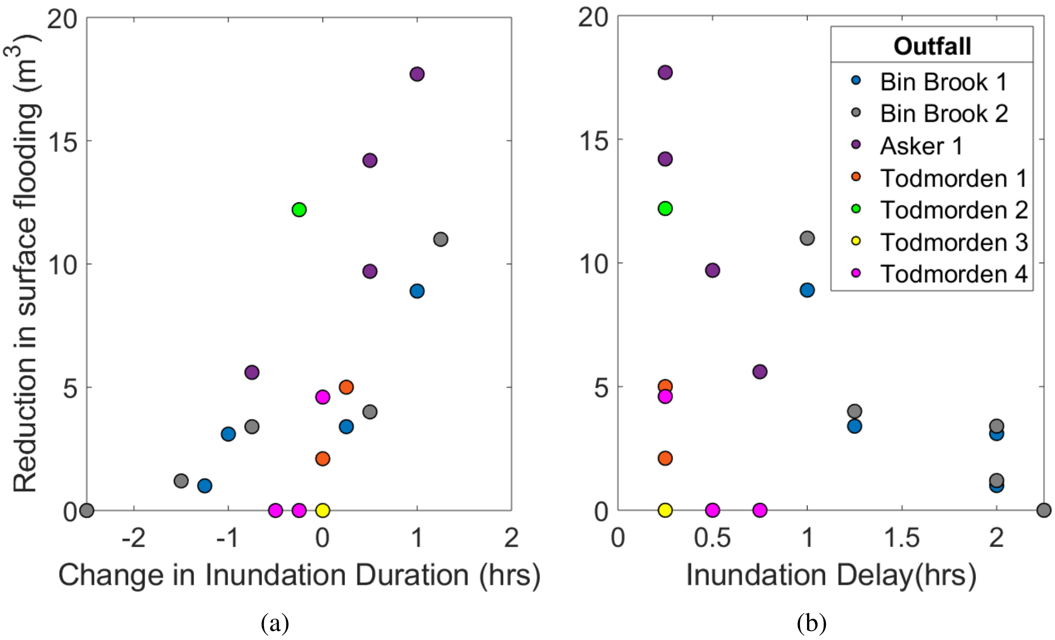


Figure 9.2 Reduction of surface flood volumes resulting from surcharged drainage across all three case studies when compared with (a) change in the inundation duration (b) delay of inundation

inundation of outfalls was completely removed by the upstream interventions (Asker 1 and Todmorden 1 during a 10 year event).

There are several instances of upstream NFM affecting outfall behaviour (i.e. reducing and delaying inundation) and thereby reducing the amount of surcharging within the drainage system. While beneficial, there is no reduction in surface flood volume and therefore these points are shown on the $x-$axis of the two plots in Figure 9.2.

Figure 9.2 (a) reinforces the earlier observation that flood reductions can occur when upstream NFM both reduces and increases the inundation duration. In fact, the figure seems to suggest that there is a broad correlation between increases in inundation duration and *greater* reductions in surface flood volume (resulting from spill from surcharged manholes). At the same time, Figure 9.2 (b) also suggests broadly that reductions are greater when the inundation delay is *smaller*.

These correlations result from the range of design intensities used to inform the two plots. During the larger design events, attenuation from NFM has been shown to diminish. This results in greater likelihood of upstream interventions slightly prolonging the time an outfall is submerged (see the 'tipping point' defined in Figure 9.1 (b)), as well as smaller delays in the onset of this inundation,. However, these smaller delays allow greater volumes pass through the drainage system before outfall inundation occurs (this is supported by the behaviour shown in Figure 6.7). In other words, while the inundation delay is smaller, the effective capacity of the system is being made greater by upstream interventions during these larger events. When the inundation delay is greater (i.e. during more frequent events), there are still reductions in the volume of surface flooding, although these are smaller because the system is under less stress.

There are still benefits during more frequent events (when delays are greater), but the baseline surface flooding is not large enough to allow upstream NFM to cause large volumetric reductions. For instance, the highest markers in Figure 9.2 are for the Bin Brook systems, where *all* of the surface flooding is removed by the max-NFM scenario for both 20 and 30 year events, but whose baselines only cause up to $3m^3$ of surface flooding.

Alongside outfall inundation, the sizes of volumetric reduction are also dependent on the local relationship between (i) the area of the contributing of the drainage system (ii) the topography of this area and (iii) the capacity within the pipes and manholes of the system. The urban drainage system in the Asker has a relatively large contributing area ($\sim 0.016km^2$), with a total transmission length (i.e. sum of all the underlying culvert lengths) of only a $\sim 60m$. As a result, outfall inundation quickly leads to the latent system storage filling to create surface flooding and subsequent NFM has greater impact (Figure 9.2 shows the greatest absolute reductions of all three case studies). The system draining to Bin Brook Outfall 2 has a larger contributing area ($\sim 0.03km^2$), but has over $250m$ of underlying drainage and this latent capacity dampens both (i) surface flood volumes and (ii) subsequent reductions achieved by NFM. This contributes to the slightly smaller reduction of $11m^3$ dispelling from this sub-system during the 100 year event (the furthest right-hand marker in Figure 9.2). The sub-system with the largest contributing area in Todmorden is above Outfall 3 (approximately $0.013km^2$), but the underlying drainage length totals over $300m$ (much of which with large diameter as discussed in section 7.4.3). It should be noted that topography also plays a role in the latent storage available for drainage surcharging – steep drainage runs will mean less of the internal storage within the upper conduits can be used before water spills onto the surface.

The trends identified in this section suggest that, by slowing the upstream rural response, NFM interventions generally allow greater volumes of water to escape urban outfalls before their inundation by local watercourses. In more intense events, more water escapes and this creates greater absolute reductions in surface flood volume. The implications of these identified trends for practitioners is discussed in section 9.5.

9.4 Widening the scope of NFM

Sections 9.2 and 9.3 focused primarily on the benefit accrued for the downstream drainage system. Section 2.4, when summarising the wider knowledge gaps identified across Chapter 2, highlighted the potential for this research to have secondary value by strengthening the argument for upstream NFM through any demonstration of influence from interventions on the rural-urban interface. Accordingly, this section will discuss how the results across Chapters 5, 6 and 7 might have implications for wider arguments in support of NFM.

Traditionally, when upstream interventions have been evaluated on their ability to attenuate catchment-scale response, the primary metric has been mitigation of downstream fluvial flood risk. However, this results in NFM effectiveness being appraised during events that are sufficiently severe to cause out of bank flow. There are two issues with this – firstly, events of this magnitude are infrequent which means the likelihood of having sufficient data to establish causal catchment-scale attenuation dwindles. Secondly, there is general agreement (both numerically and physically) that the impact of interventions will diminish with increased storm intensity (Dadson et al., 2017).

Figure 9.3 compares how the max-NFM scenario reduces peak magnitudes in each of the three case study catchments. The figure also indicates the onset of both (i) outfall inundation and (ii) fluvial flooding.

Firstly, it is interesting to compare the impact of the max-NFM scenario of peak flow reduction across each catchment. All three case studies have made conjectures based on transformative change in rural land management practices with large areas of afforestation and channel modification. However, clearly this has been most effective in the Asker catchment and least effective in the Calder catchment.

It is hypothesised that there are at least two reasons for this. Firstly, it has been suggested that gentle topographies (such as those in the Asker catchment) are better suited to both tree planting (Nisbet et al., 2011) and woody debris (Manners and Doyle, 2008). Alongside this, while only 20% of the catchment is afforested in the max-NFM scenario, this equates to a $\sim 10km^2$ intervention (the largest of all three). The max-NFM scenario in the Bin Brook case study contains tree planting across 79% of the catchment, which equates to $\sim 8km^2$ of afforestation. However, it is also possible that the very shallow topography of the lowlands catchment might inhibit the effectiveness of the intervention. The Calder catchment sees 24% of the catchment afforested under the max-NFM scenario (an area of $\sim 5km^2$). Not only is this significantly less coverage, the very steep topography may limit the ability of the intervention to attenuate flow effectively.

Secondly, Figure 9.3 shows the magnitude of intervention impact before and after fluvial flooding begins to occur in each of the downstream urban areas. This clearly demonstrates

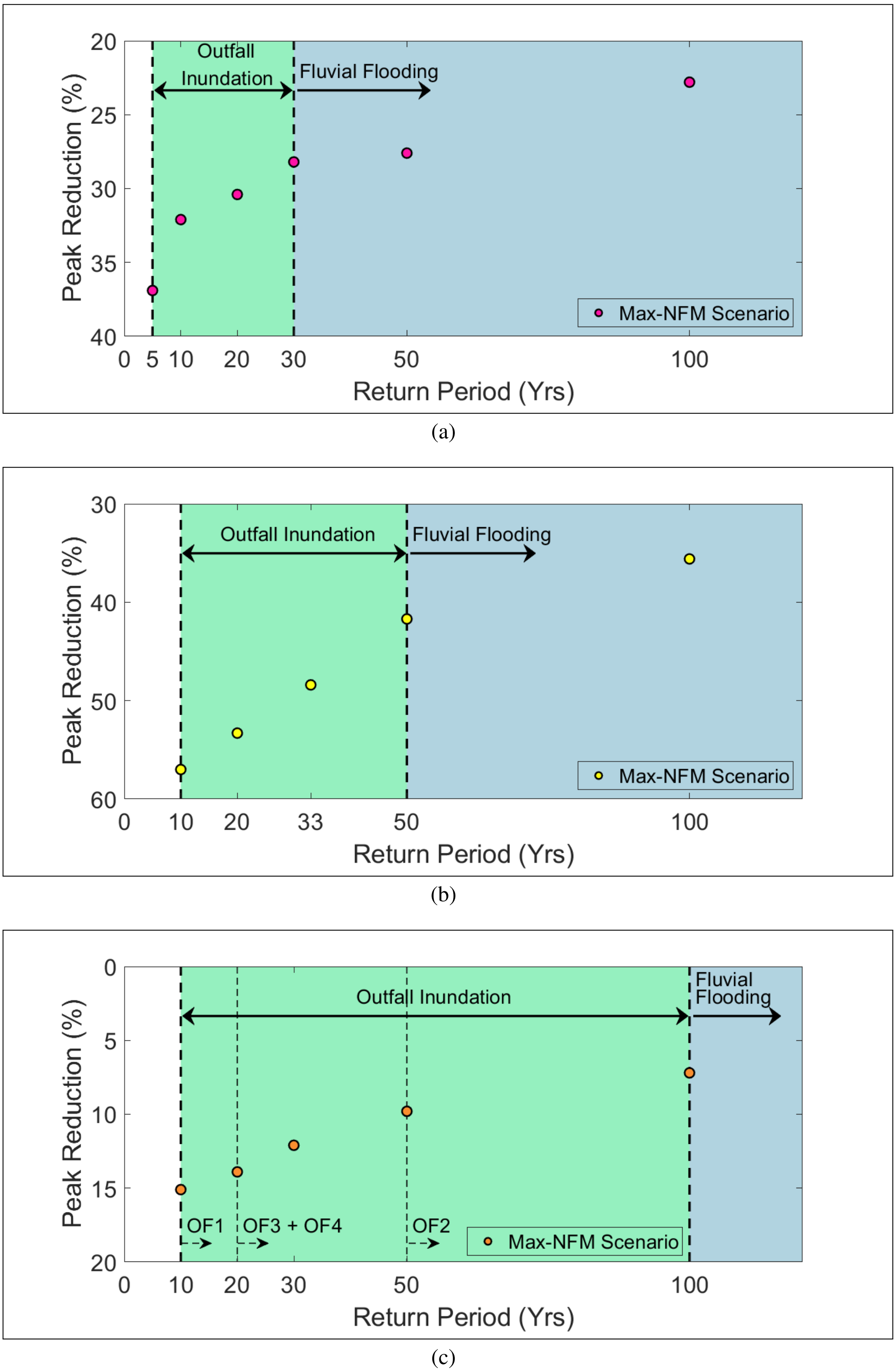


Figure 9.3 Changes in peak reduction resulting from the max-NFM scenario across multiple storm events (along with indication of on-set of fluvial flooding) for (a) Bin Brook catchment (b) Asker catchment and (c) Calder catchment

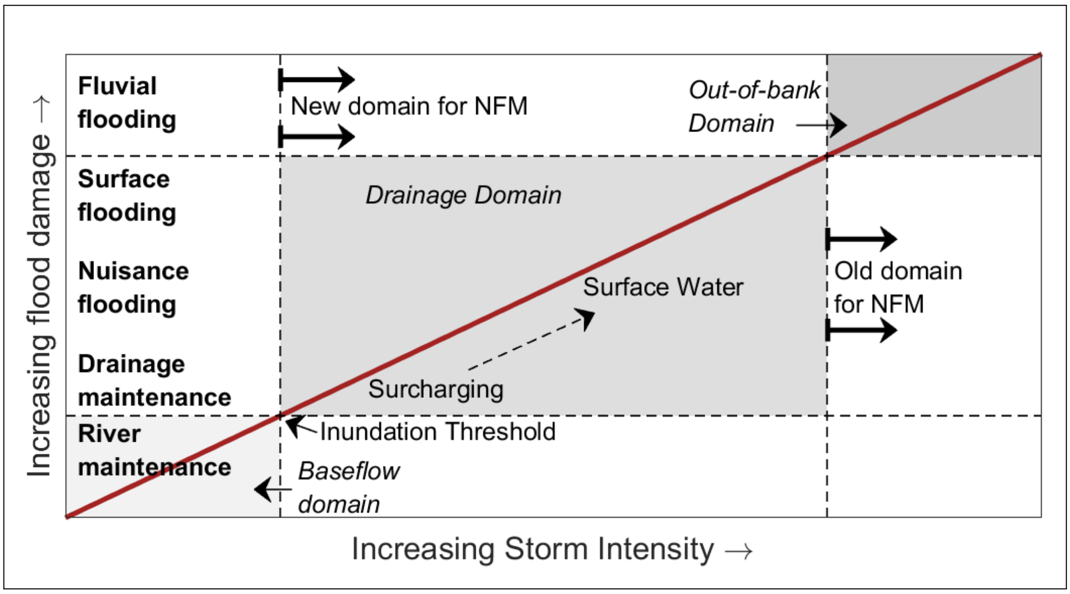


Figure 9.4 The Three Points Approach framework (adapted from Fratini et al. (2012)) with regards to the expansion of the typical domain used to evaluate upstream NFM interventions

that interventions are having greater impact *before* fluvial flooding begins to occur. Until now this influence on catchment-scale flow has not been widely identified as being of benefit. However this research (and Figure 9.3) illustrates there is potential for tangible benefit during less severe events.

The results in Figure 9.3 inform the generalised conceptual relationship given in Figure 9.4. To do this, Figure 9.4 modifies the Three Points Approach (TPA) developed by Fratini et al. (2012) which identifies three modes of operation for urban drainage infrastructure as storm severity increases: (1) within design capacity, (2) a managed exceedance phase and eventually (3) uncontrolled flooding. The approach has become widely recognised in the literature (Hoang and Fenner, 2015; Lerer et al., 2017; Sørup et al., 2016). This delineation of operational states can be modified to demonstrate how this research expands the range of events under which upstream NFM could be evaluated for mitigation of downstream urban flood risk.

Figure 9.4 compares increasing storm intensity and increasing costs of resultant flood damage. In very low storm intensities, the only costs accrued are in properly maintaining the river channel. This has been termed the ‘Baseflow Domain’. The results of this study have shown that (in certain cases) as storm severity increases, an ‘inundation threshold’ is reached when drainage outfalls become inundated. This point delineates the lower bound of the ‘Drainage Domain’. From this point, storms can begin to cause surcharging of drainage systems. As a result, costs rise to include drainage maintenance. As storm intensity increases further, this surcharging can lead to nuisance flooding. The associated costs of this nuisance flooding are typically related to the maintenance or operational costs for road carriageways. Beyond this, the research has shown there is potential for significant surface water volumes (see Figure 7.7), where damage costs will rise significantly. Figure 9.3 identifies the thresholds at which fluvial flooding will begin to occur for each of the case studies. Beyond this threshold is termed the ‘Out-of-bank domain’ when fluvial flooding will potentially lead to significant costs. Figure 9.4 also highlights the broader domain of event severities where NFM could play a role in mitigating downstream flood risk (marked ‘New Domain to NFM’ in the figure).

The implications of this for practitioners are discussed in section 9.5, although it should be noted that, while all three case studies have exhibited behaviour following the relationship given in Figure 9.4, this is dependent on local geometry and conditions. There are also other sources of uncertainty which could obfuscate the generalised sequence; these will be discussed in section 9.6.2.

9.5 Applicability of results for practitioners

The trends identified in sections 9.2, 9.3 and 9.4 are subject to significant uncertainty (discussed in section 9.6.2), but still have implications for the design and operation of both surface drainage and NFM.

This section begins by using the results to offer specific recommendations for each case study catchment, based on local circumstances (see Chapters 5, 6 and 7). Section 9.5.2 then proposes a ‘risk profile’ for outfalls to demonstrate how the trends identified above could be of interest and value to a wider group of flood risk practitioners.

9.5.1 Recommendations for case study catchments

Each of the case studies will now be discussed separately.

- **Bin Brook catchment:** Nuisance flooding resulting from drainage surcharge has been anecdotally reported by residents of Gough Way and the results here (Table 5.2) suggest this could be largely mitigated by extensive upstream NFM. However, this is overshadowed by significant fluvial flood risk (shown in Figure 9.3 (a)), much of it resulting from the undersized culvert. The results suggest this fluvial flood risk should dominate the design objectives for any upstream NFM. To this end, Figure 5.4 suggests the tree planting intervention would be better in alleviating downstream peaks.

However, in such a small catchment, it is feasible that lumped storage could achieve a similar effect (see section 9.7.1 for further discussion). The broader trends identified in sections 9.2 and 9.3 suggest that any attenuation achieved would also have benefit for drainage performance – this could be incorporated into a cost benefit analysis to further strengthen the case for implementation.

- **Asker catchment:** There is clearly a significant risk of nuisance flooding in the residential area of Bridport focused on in this research (see Figure 6.2). The results suggest that inundation of outfalls could be contributing to this risk. There also appears to be scope for significant attenuation of the rural response using upstream NFM (see Figure 6.6). However, the extent of the max-NFM scenario and resultant modest benefits seen downstream (shown in Figure 6.8) are unlikely to justify physical implementation (see section 9.7.3 for further discussion on this issue). Without wider momentum (and justification) for NFM across the Asker catchment, there is little incentive for Wessex Water (the local water company) to seek support for physical implementation. There could be alternative solutions to the risk posed by inundated outfalls, such as additional engineered storage within the drainage system (although this would likely have no wider benefit).
- **Calder catchment:** The peak attenuations seen for this catchment were the least of the three case studies examined (Figure 9.3). Despite this, this attenuation offers perhaps the strongest argument for using NFM to improve surface drainage. This argument is threefold. Firstly, Yorkshire Water have explicitly attributed outfall inundation to exacerbated local flood risk. Identifying this mechanism stimulates consideration of mitigation methods. Secondly, although the urban model used in this research sees no fluvial flooding until the 100 year event (see Figure 9.3 (c)), beyond its domain further downstream there is significant fluvial flood risk. As section 7.2.1 describes, this has incentivised investment and implementation of NFM to slow the flow around the upper Calder. Thirdly, as Figures 7.7 and 7.9 illustrate, attenuation of catchment response can have benefit across four different sub-systems through Todmorden (rather than the single system in Bridport).

9.5.2 Wider implications of trends for practitioners

This study has partnered with local stakeholders (e.g. Yorkshire Water), conducted extensive desk studies and used local knowledge (e.g. the Gough Way residents association) to select and help investigate the three case study catchments. These factors introduce a form of bias into the research, in that it does not explicitly investigate the wider likelihood of outfall inundation in other catchments around the UK. This is exceedingly difficult to examine because of the dependency of the inundation threshold on local conditions.

However, the results imply that urban flood management practitioners could benefit from greater consideration of the rural-urban interface (defined in Figure 1.1). By highlighting the potential for surface drainage performance to be a responding variable to upstream rural interventions, the research demonstrates value in widening the scope with which these systems are scrutinised and solutions evaluated.

The trends identified in sections 9.2, 9.3 and 9.4 provide practitioners with the opportunity of a 'risk profile' that would (i) identify the likelihood of outfall inundation for any given outfall in any given catchment and (ii) offer a high-level understanding of how upstream NFM might influence the drainage performance of that outfall over a range of different storm events.

Figure 9.5 offers a idealised example of a plot that could be applied to any downstream urban watercourse. The $y-$axis is the vertical height above the urban channel invert, normalised between a datum 0 (the channel invert) and 1 (when water level overtops banks to cause fluvial flooding). The trends reported in section 9.4 (and generalised with a modified

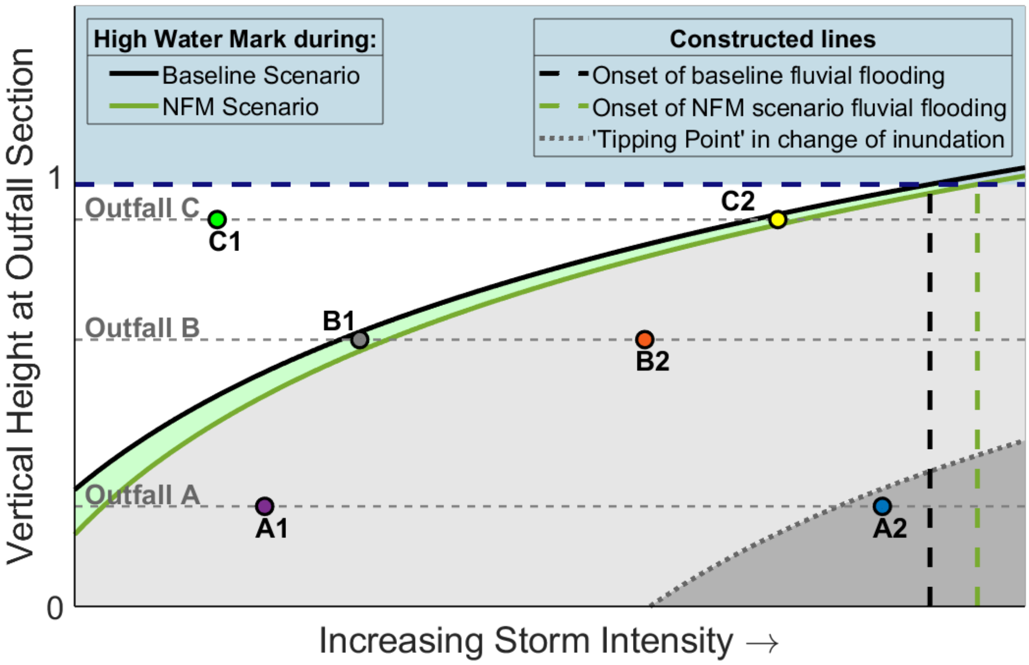


Figure 9.5 Example Risk Profile for assessing the likelihood and consequence of inundation of outfalls and the subsequent impact of upstream NFM

three point approach in Figure 9.4) highlighted this as the novel domain within which to evaluate benefit from upstream NFM interventions.

For this (normalised) height scale, any catchment rainfall event will have a ‘high water mark’ (i.e. highest water level at that section). Figure 9.5 presents a hypothetical relationship for this high water mark as storm intensity increases along the $x-$axis (the upper curve). This normalised relationship will exist for all downstream urban watercourses, although its precise shape will be dependent on (i) the local geometry at outfall and (2) the characteristics of the upstream catchment.

Any attenuation of the catchment’s flow response achieved by upstream NFM interventions will result in a slightly lower high water mark for any given storm intensity (depicted by the green curve on Figure 9.5). The form of this relationship will be dependent on the characteristics and effectiveness of the upstream intervention, although evidence suggests the greatest impact will be at lower storm intensities with height reductions diminishing as levels increase to the fluvial flooding threshold.

The area between the two curves (in light green) depicts the domain for which upstream interventions *completely* remove inundation of an outfall. This domain narrows as storm intensity increases because of the diminishing attenuating impact achieved by these interventions.

As storm intensity increases, any given outfall height will begin to be inundated during the NFM scenario as well (the light and dark grey area in Figure 9.5). Within this domain, the outfall will be affected by the change in inundation duration created by the upstream interventions. As has been discussed, this change can be a reduction (the light grey area) or, as storm severity increases, can begin to lead to a prolongation of outfall inundation (the dark grey area). The lower the outfall, the more susceptible it is this prolongation effect. The onset of prolongation (a given storm intensity) is defined in section 9.2 as the ‘tipping point’. A construction is used to hypothesise the tipping point across various outfall heights in Figure 9.5 (in reality, a practitioner would require significant modelling to establish its exact form – as demonstrated by Figure 9.1 (a)).

Within Figure 9.5, the inundation experience of an outfall (and consequent impact from NFM) during any particular storm intensity can be represented with a single point. A flood risk management practitioner (from either an NFM implementation background or from a surface drainage design background) can see how an outfall behaves (under baseline and upstream NFM scenarios) across a range of events using a horizontal line.

Three hypothetical outfalls are given in the figure. Outfall A is the lowest and is inundated by the most frequent storms. At point A1, the storm intensity is such that the outfall becomes inundated, but NFM reduces this inundation. At point A2 the storm intensity is high enough that the tipping point has been passed so that NFM is now increasing the inundation. Outfall B is higher and remains freely discharging for longer. At point B1, the storm intensity is such that inundation of this outfall is removed by the upstream NFM scenario. Point B2 remains inundated, but this inundation is reduced (i.e. the tipping point is not reached). Outfall C is the highest and is not inundated until storm intensities approaching those that cause fluvial flooding. Point C2 experiences the same effect from the NFM scenario as B1, but it is worth noting that this domain is much smaller at higher intensities (because upstream NFM interventions are having a smaller attenuating effect on the high water mark).

In summary, upstream NFM will have benefit for inundation duration in two ways. Inundation can be removed (the narrow green domain on the diagram) or, in higher intensity storms, reduced (the light grey domain).

Interestingly, this conceptual risk profile could also be used by a practitioner to ensure that any upstream intervention does not cause an outfall to reach a tipping point before onset of fluvial flooding. This would be done by demonstrating that the tipping point construction line crossed the lowest outfall line *beyond* the storm intensity at which fluvial flooding occurs (under the NFM scenario).

Figure 9.5 presents a conceptual risk profile for understanding how outfall inundation could be affected by upstream NFM. By normalising the $y-$axis, it could be applied to any local geometry. By using storm intensity on the $x-$axis, the profile can be applied regardless of differing upstream catchment characteristics (e.g. size, topography, geology, land use etc.). Even so, it should be recognised that Figure 9.5 presents a highly idealised case and does not account for factors such as: sedimentation below the outfall, failure of upstream interventions or multiple storm events.

Separately, while the inundation duration of outfalls is clearly important, the trends identified in section 9.2 about inundation *delay* suggest that if an outfall is inundated (i.e. below the upper curve on Figure 9.5), any slowing of the upstream rural response will be beneficial for the performance of the drainage contributing to the outfalls. Nonetheless, the outfall risk profile concept could have significant benefit both NFM and surface drainage practitioners, allowing clear identification of how behaviour of outfalls might be affected by local watercourses and then alleviated by upstream interventions.

The underlying uncertainties in the methodology will now be re-evaluated to understand how they may impact these trends and recommendations.

9.6 Reflection on coupled methodology

This chapter has so far attempted to examine the results across the three case studies in order to identify trends which could be extrapolated to and tested with other catchments. This section will highlight and evaluate the key assumptions made which temper the research's ability to offer these broader conjectures. The approach to this will be twofold – section 9.6.1 will evaluate the effectiveness of the coupled model in producing the results, section 9.6.2 will evaluate key sources of error impacting on the confidence of the identified trends.

9.6.1 Calibration and usage of coupled model

Chapter 3 justified the coupled modelling methodology (consisting of Dynamic TOPMODEL, HEC-RAS and Infoworks ICM) used to obtain the results which inform this discussion chapter. Section 3.12 evaluated the potential error sources within the methodology. However, following its application, there are several aspects of its calibration and NFM representation which justify further reflection.

9.6.1.1 Calibration

Figures 5.3, 6.4 and 7.5 compare the observed and simulated flow resulting from each of the respective calibrations of the coupled Dynamic TOPMODEL and HEC-RAS components. It is interesting to note that the Nash Sutcliffe Efficiency (NSE) of each of these three calibrations is 0.83. This could be coincidence but it is worth re-visiting their respective methodologies to understand if the coupling or calibration procedure (although justified by other literature) has inadvertently been 'self-limiting'.

On closer inspection, one potential cause of this could be the consistent under-prediction of baseflows within the calibrations. Section 3.12.1.2 discusses the inherent biases of the NSE calculation, but the causes of base flow underestimation could be varied.

Firstly, these causes could stem from the coupled model's structure. Dynamic TOPMODEL and HEC-RAS may not be numerically replicating sufficient storage within the hydrological system. Alternatively, it is possible that assumptions made in the coupling method are a factor. The loose couple (described in section 3.7) means that the input into HEC-RAS does not distinguish between surface and sub-surface contributions and is not affected by water levels in the channel. This could result in lower flows during dry spells (such as those seen in the calibration period).

Secondly, it is possible that the calibration procedure itself is 'self-limiting'. The Dynamic TOPMODEL Monte Carlo calibration procedure was set up to favour those simulations replicating peak flow magnitudes (see section 3.10.3), which could discriminate against parameter sets with accurate base flow prediction. The structure of the coupled model would mean this bias would be carried through the downstream HEC-RAS model.

A final factor could be issue with the contributing data. The Thiessen polygons homogenise rainfall and isolated gauges are not sufficiently capturing intervening rain showers. Additionally, the constructed rating curves used to translate level gauge data (discussed in detail in section 3.12.1.2 and given in Appendix B) could be resulting in an over-prediction in flows.

9.6.1.2 Representation of NFM

Although justified, the numerical representation of NFM introduces significant uncertainty over downstream impact (and consequentially impact on outfall inundations).

Tree Planting

Section 3.8.1 justifies the representation of tree planting within Dynamic TOPMODEL's parametrisation of the hydrological system. However, the influence of each of the parameters on downstream impact deserves further attention.

Figure 9.6 gives the results of a sensitivity analysis of the parameter shifts used to represent the tree planting component of the max-NFM scenario in the Calder catchment (extent of the intervention is given in Figure 7.1). The analysis consisted of shifting each parameter independently while leaving the other three as calibrated. This allowed greater understanding about how each constituent scaled parameter contributed to the overall modelled intervention.

The parameter ranges given in Figure 9.6 were justified for T_0 and v_{of} (Hankin et al., 2016) and m (Coulthard and Van De Wiel, 2017). The range of shifts for srz_0 were hard to justify (none having been explicitly given elsewhere) but the figure demonstrates that the srz_0 parameter is the least effective in attenuating the calibration's peak magnitude flow. It is hypothesised that this is because the storage is overwhelmed by rainfall prior to the peak event. The v_{of} parameter offers marginal reductions, which increase as the tree planting factor reduces from 1. The catchment response during the calibration period sees minimal overland flow, which is possibly one reason why alterations to this parameter do not have greater impact. The two parameters that have greatest impact are those used to define lateral hydraulic conductivity through the soil – T_0 and m. As both tree planting factors increase away from 1, there is greater attenuation of downstream peak magnitude.

The implications of this sensitivity analysis are that m is the dominant parameter in the representation of tree planting. Previous TOPMODEL studies that have found m a highly critical parameter in calibration (Kim and Delleur, 1997; Molicova et al., 1998). As the

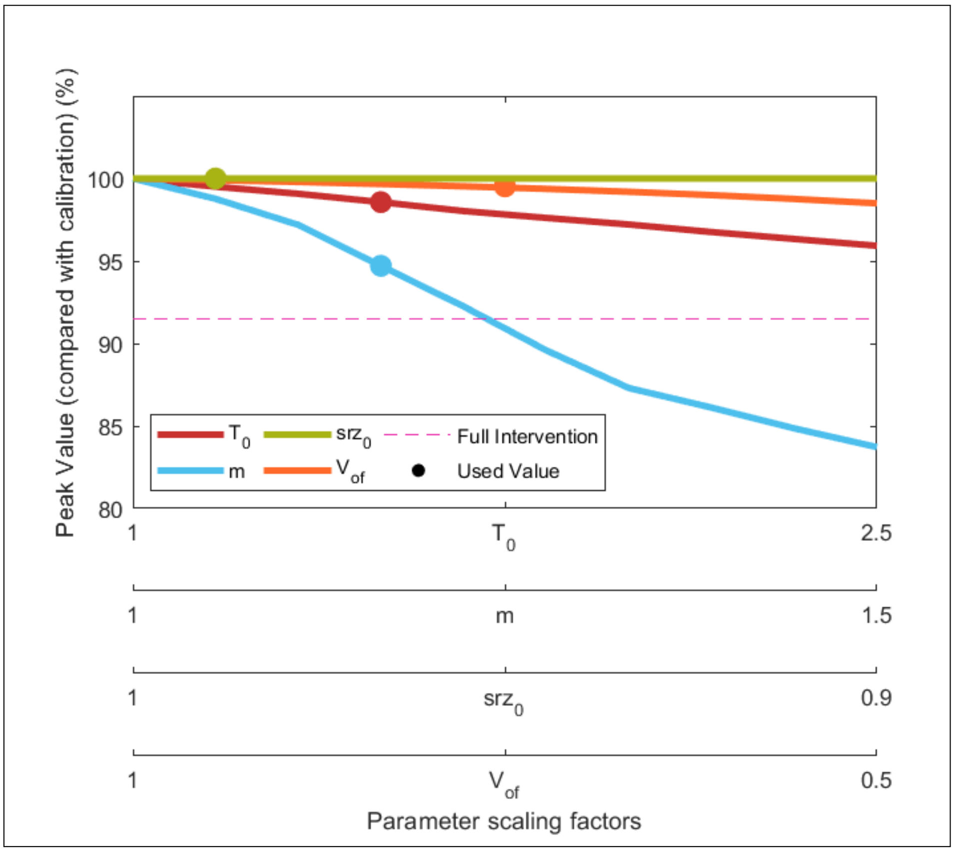


Figure 9.6 Sensitivity of parameter shifts used to represent max-NFM scenario tree planting in the Calder catchment

parameter continues to increase (to values used in both Coulthard et al. (2000) and Coulthard and Van De Wiel (2017), the tree planting intervention will cause greater attenuation. In doing so, the intervention will have greater impact downstream on outfall inundation and surface drainage performance.

It should be highlighted again that this sensitivity analysis of parameters sits within the assumptions made by the underlying model structure. Different structures will parameterise impact differently and produce different outcomes. However, the parameter shifts used here (shown in Figure 9.6 and justified in section 3.8.1) generate modest downstream attenuation, in line with other studies modelling the catchment-scale impacts of tree planting (Dixon et al., 2016; Iacob et al., 2017).

In-channel woody debris

Section 3.8.2 justified the representation of woody debris through alteration of the Manning's *n* value. This representation has been extensive precedent (Adams et al., 2019;

Curran and Wohl, 2003; Dixon et al., 2016; Odoni and Lane, 2010; Rasche et al., 2019; Thomas and Nisbet, 2007). However, the hydraulic behaviour of such physical structures typically involves constricting flows beyond a certain threshold to create a backwater effect and storage within the riparian zone (discussed in Thomas and Nisbet (2012)). This storage routing effect is not captured by increasing Manning's n.

However, a review by Addy and Wilkinson (2019) highlights the fact there is insufficient evidence to confidently assign depth-discharge relationships to such structures (again largely because of the unique characteristics of individual channels). One option could be to use the equation presented in Kirschmer (1926) for headloss across a bar grill. Alternatively, Metcalfe et al. (2017) uses underflow barriers with low flow governed by equations from Swamee (1992) and any overtopping governed by a weir discharge equation. This highlights the range in potential representation of in-channel woody debris, along with the required complexity of appropriately capturing their behaviour.

Alongside this, the representation used here assumes artificial placement of wood in the channel (as done in a physical study reported by Addy and Wilkinson (2016)). It also does not consider the probability or impact of structural (or even cascading) failure. This is a significant cause for concern. Firstly, because this will reduce probability for a tipping point being reached at downstream outfalls (as discussed in section 9.5) and secondly because such movement can lead to exacerbated flood risk (Curran, 2010; Pagliara and Carnacina, 2011).

In summary then, the representation of in-channel woody debris is a pragmatic (and conservative) approach which achieves a feasible degree of downstream attenuation. It could, however, be represented more 'realistically' by better capture of structure hydraulics.

9.6.2 Influence of uncertainty on identified trends

Beyond the limitations just described about the calibration procedure and representation of NFM, other methodological choices will have introduced some uncertainties to the trends identified in sections 9.2 to 9.5.

In Chapters 5 to 8 it was stressed that the results presented cannot be treated as the absolute effects of physical upstream interventions within the case study catchments. As argued in section 3.12 – the purpose, focus and novelty of the coupled approach has necessitated assumptions and methodological choices which mean the results should be treated with caution. That section also put forward the case behind focusing on gaining an indicative understanding of how plausible upstream attenuation from natural interventions could improve surface drainage performance.

One source of potential error affecting the trends reported within this chapter is the use of uniform rainfall in their derivation (as demonstrated by the results set out in 8.3). Spatially varying rainfall has been shown both to alleviate and to exacerbate the repercussions of outfall inundation (and consequently the impacts derived from upstream NFM). Despite this, in all the rainfall patterns and intensities evaluated, slowing of the rural response continued to have modest benefit for downstream drainage performance. Theoretically however, it would be possible for delayed outfall inundation to coincide with further events and exacerbate flood risk.

This leads on to a further key source of uncertainty when interpreting the trends – the use of idealised, single pulse design storms. This assumption has several consequences. Firstly, the effectiveness of the upstream interventions will be dependent on the hyetograph's shape (see in Figure 5.4 for how attenuating impact differs between the calibration peak and the comparable design events). Secondly, this form of rainfall also heavily influences the timing and form of the urban response (see Figure 6.7 for an example of this), meaning drainage performance is influenced in a particular way. Thirdly, the antecedent condition for the urban drainage is a dry system (meaning maximum potential latent storage for the single design event). Section 9.7 offers a discussion on how future research could incorporate multiple events into the analysis.

It should also be recognised that this research has primarily considered failure resulting from outfall inundation creating surcharge within the drainage system. The results in Chapters 5, 7 and 8 rely on reporting flood volumes which result from this phenomenon. In reality, these volumes could contribute load to other manholes within the system (through overland flow). Furthermore, other forms of failure – including surface ponding or another form of blockage – will have a large influence on overall performance. These factors would further obfuscate the upstream impact from NFM and indeed, within a poorly designed system, continued free discharge through outfalls is unlikely to be sufficient to significantly improve performance.

Finally, there were several assumptions which alter numerical outfall behaviour from what would be observed. It has been assumed that inundation occurs when the receiving watercourse rises above the outfall invert level. This was to avoid significant computational complexity and was deemed acceptable because the rising limb of the rural hydrograph will typically very quickly rise across the vertical face of the outfall. It is also a conservative assumption as it means more water will be trapped for longer within the system. However, water will still be able to escape as water rises up the outfall. Also, in sufficiently steep urban catchments, sufficient head could be developed through the drainage system to force water through the outfall under hydrostatic pressure, creating more effective capacity within the system. Overall then, the baseline cases may be slightly over-predicting the volumes trapped by outfall inundation. As a result, the modelled impacts of NFM might be smaller than those reported on in this chapter.

The methodology, in taking pragmatic decisions to focus on the central research question, retains potential sources of error which should be recognised alongside the generalised trends presented earlier in the chapter. Therefore, treatment of impacts and effects from upstream NFM should not be taken as absolute.

It is recognised that further work is needed to examine additional permutations that this work has identified (e.g. varying rainfall, other forms of NFM, other catchment situations) as well as to identify realistic ways of reducing some of the identified sources of error, including giving continuing attention to on-going improvements in relevant modelling software.

This potential for further work will now be discussed extensively in section 9.7.

9.7 Further Areas of Study

This section will discuss three different directions that further research could take to develop further evidence related to the central research question. Such research (for example on de-synchronisation) might also be pertinent to some other arguments that are put forward in support of NFM.

9.7.1 Further evaluation of upstream interventions

As discussed in section 2.2.4, the role of modelling in the physical implementation of NFM is now receiving increased scrutiny. Despite the nascent physical evidence base, there is potential for modelling to contribute to greater understanding of intervention impact and catchment-scale design.

The principal requirement for overcoming the challenges faced when modelling NFM is undoubtedly further physical gauging within catchments. The benefits of this would be twofold. Firstly, more data could be used to inform construction and calibration of underlying hydrological models. Secondly, pre- and post-implementation gauging (at a variety of scales) is necessary to build confidence in NFM impact.

This research has shown that modelling can still have a role in the evaluation of upstream NFM. The representation of the two forms used in this research has been extensively discussed – but section 2.2 highlights the variety of different types of intervention opportunities. There could be scope for using these to achieve similar impacts to the 'max-NFM' scenarios, without requiring the transformative change conjectured here. It has been argued by others that creating storage in the catchment's hydrological system through disparate ponds offers the most certain way of influencing response (Nicholson et al., 2020). In smaller catchments such as the Bin Brook, this could offer a feasible method for attenuating catchment-scale response, although the placement of this intervention could become critical. In larger catchments, more storage is needed to have similar effect but perhaps each intervention might need less emphasis placed on its location.

One fascinating avenue would be to determine the role real time control (RTC) could play in the efficiency of such disparate storage. By incorporating radar into the control of different levels across several ponds, it might be possible to control the antecedent level in ponds (using penstock actuators) to create tributary de-synchronisation in real time. This could result in the development of 'smart catchments' which use a spectrum of green and grey infrastructure to attenuate catchment-scale flow.

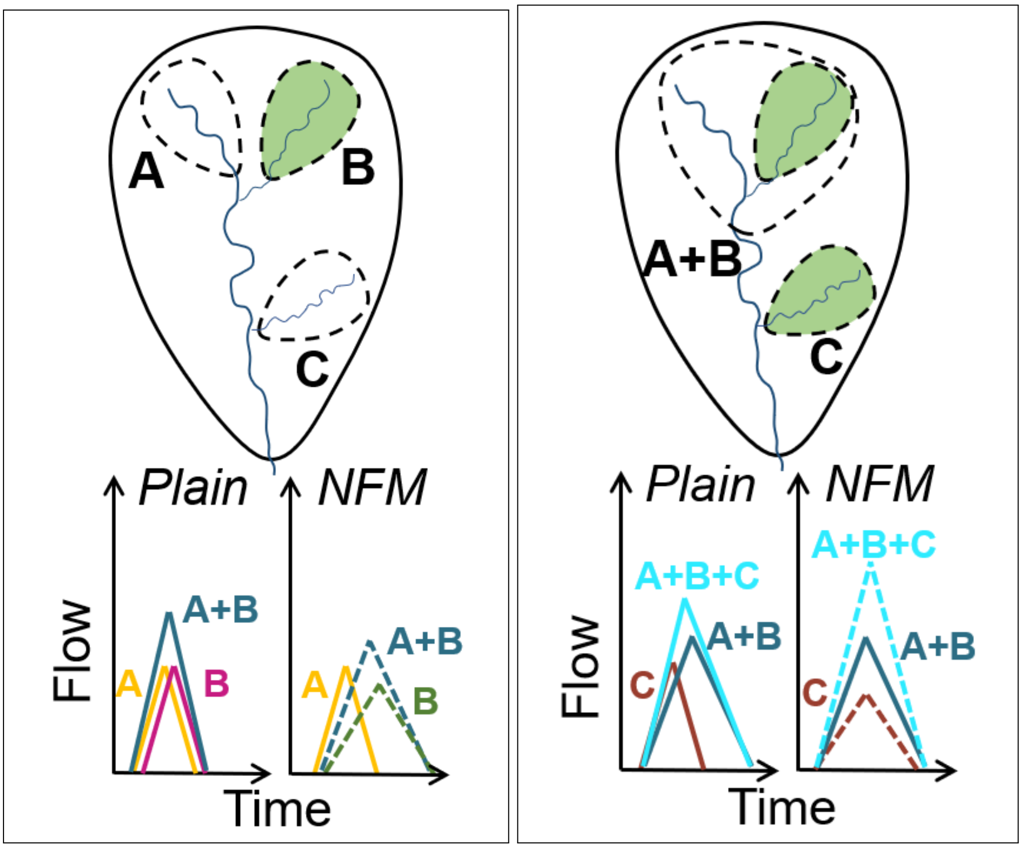
The results also suggest that the hyetograph shape has a significant impact on the effectiveness of interventions – understanding performance thresholds across different storm profiles (with same return period) would extend the knowledge base. Furthermore, there has been very little direct comparative work done on a single intervention form across multiple catchments (similarly to that done for tree planting within this study as shown in Figure 9.3) (Dadson et al., 2017).

There is also potential for significant work in the catchment-scale design of interventions – section 2.2.2 discusses the interest in using NFM to desynchronise tributary response. This is another (potential) alternative in achieving the impact of a max-NFM scenario, without requiring the same extents of intervention. To this end, further research into identifying 'target' sub-catchments would contribute to the evidence supporting catchment-scale impact. This has been recognised as being critical for catchment-scale impact from NFM, although very little work has been done in this area (Pattison et al., 2014).

Figure 9.7 aims to illustrate the complexity behind this problem with a hypothetical catchment response. In Figure 9.7 (a), slowing the flow in a single sub-catchment creates de-synchronisation of tributary responses feeding the upstream confluence. In Figure 9.7 (b) this attenuation upstream feeds into a second confluence. However, in this hypothetical catchment, slowing the response of catchment C now synchronises the two contributory flows, exacerbating downstream flow magnitudes.

This is a simple conceptual model, but when scaled up to physical catchments such consideration becomes very complex. It is further complicated by variable storm tracks resulting in sub-catchment response timings being potentially unique to the spatial rainfall pattern (as found at a catchment scale in section 8.3). The coupling of Dynamic TOPMODEL and HEC-RAS (as demonstrated in this research) could offer a very effective tool for such analysis, although perhaps with an alternative stochastic approach to storm timing.

The results in section 8.3 also raise the interesting possibility of identifying catchments where using NFM to desynchronise rural and urban response could have greatest benefit. They suggested that a rain event crossing the rural environment before reaching an urban area would result in the two responses being most closely aligned. In catchments with prevailing winds creating this situation, the desynchronisation from upstream NFM could have greatest impact on drainage performance. Conversely, in catchments where the prevailing wind results in rainfall falling on the urban area first could see minimal effect. This behaviour has only been evaluated on a single catchment and would require wider interrogation before definitive recommendations could be given.



(a) (b)

Figure 9.7 Hypothetical example of NFM being used to mitigate catchment response through tributary de-synchronisation and having a (a) beneficial and (b) detrimental impact

9.7.2 Patterning of Events

The use of single pulse, idealised design storms has been an acknowledged source of uncertainty in this work (see section 9.6.2). The evaluation of interactions across the rural-urban interface would benefit from a more sophisticated consideration of rainfall.

This could take the form of multiple, phased design storms to gain better understanding of the role the antecedent drainage state has, as well as potentially identifying negative repercussions from delaying outfall inundation. The creation of multiple events has also been achieved using Poisson distributions (as first put forward by Rodriguez-Iturbe et al. (1987)). Wheater et al. (2005) offers a review of stochastic representation of variable rainfall at a daily scale (and Kossieris et al. (2018) develops a disaggregation scheme for sub-hourly application). It could also be possible to evaluate changes in drainage performance using extended periods of observed data.

It is hypothesised that different rainfall patterns could substantially influence conclusions. Urban rainfall occurring during periods where outfalls are inundated could significantly exacerbate the risk of drainage surcharging and surface flooding, particularly in systems with less latent capacity.

Figure 9.2 highlighted the importance of inundation delay (when evaluating NFM impact). However, it is conjectured that, with more sophisticated rainfall patterning, the importance of changes in inundation duration could be fully recognised. However, there would also be changes in the ability of upstream interventions to attenuate flows.

9.7.3 Economic Feasibility

The critique of the economic (or practical) viability of using NFM to improve drainage performance has not been a primary focus of this study.

The adoption of NFM has been constrained by a somewhat circular argument, in that the evidence base in relation to its impact on fluvial flood risk remains limited by insufficient physical implementation and monitoring. However, the financial backing needed to conduct this monitoring and feedback is inhibited by the embryonic evidence base.

Therefore, as explained in section 2.2, justification for an NFM intervention, especially within multidisciplinary CMPs, often relies on the argument for accumulated multiple benefits (e.g. water quality, biodiversity, public amenity etc.). This research has identified a further (previously unrecognised) benefit in relation to gains for downstream drainage systems. This lends additional support for CMPs and other interested bodies in particular catchments to make their case for new NFM projects. However, the modest impacts which might be expected to accrue from such transformative interventions, while undoubtedly strengthening the argument, are unlikely, on their own, to justify financial backing for physical implementation.

Nonetheless, there could be benefit in attributing financial value to the impact achieved. Although somewhat controversial, natural capital philosophies allow comparative cost benefit analyses with more traditional solutions. Both Dixon et al. (2018) and Short et al. (2019) point out their importance for implementation managers and Catchment Management Partnerships have been known to run natural capital appraisals for their own interventions (Davies et al., 2020).

One such tool is B£ST (Benefits Estimation Tool), which is freely available from CIRIA[1], offering a high-level economic assessment of the multiple benefits accrued from blue-green infrastructure. Although traditionally used to appraise SuDS (Hamann et al., 2020; Kapetas

[1]https://www.susdrain.org/resources/best.html

and Fenner, 2020), it was expanded in 2019 to include NFM interventions. The tool's preliminary coarse assessment (based on factors such as air quality, biodiversity, flood risk and recreation) was applied to the three case study mas-NFM scenarios (i.e. catchment-scale tree planting and in-channel debris). Along with the assumptions of the tool, the assessment assumed (i) only properties within $30m$ of the nearest manhole to each outfall would achieve a small flood risk reduction and (ii) the woody debris intervention would contribute to enhancing the in-channel ecological status. The study found approximate (central estimate) benefit of £$15,800$, £$20,400$ and £$10,200$ for the Bin Brook, Asker and Calder catchments respectively. The biggest contributing benefit was carbon sequestration, accounting for 96%, 93% and 93% of the totals for the three catchments.

These were crude, high-level calculations. However, they offer insight to the contributory role multiple benefits could play in building an economic case for upstream interventions. More developed calculations could be compared with the costs and benefits accrued from alternative solutions to outfall inundation in the urban area (e.g. engineered or SuDS storage) to better understand the economic viability of slowing the flow upstream.

9.8 Summary

This chapter has used the results from three case studies to identify trends which will be of interest and possible benefit both to those working in NFM and to practitioners in urban flood management. The latter might find the outfall risk profile diagram offered in Figure 9.5 which links NFM intervention with drainage performance to be of particular value.

A short, concluding chapter will now reflect on the success of this research in answering the central research question presented in section 1.2.

Chapter 10

Conclusions

The central research question asked: *what effect can catchment-scale NFM interventions have on the performance of downstream urban surface drainage systems?*

The context and significance of this question are set out in Chapters 1 and 2. The novel methodology developed to build a response to the central research question and its sub-questions is discussed and justified through Chapter 3. Chapters 5 to 7 present the results from application of this methodology in three separate UK catchment case studies. These are augmented by Chapter 8, which further interrogates two identified dependencies – the effects of climate change and variable storm track. Chapter 9 infers and discusses broader trends seen in the results from all three principal case studies.

This final chapter closes this thesis by first responding directly to the sub-questions listed in section 1.2 before offering final conclusion on the central research question.

Sub-Question 1: What attenuating impact does upstream NFM have on the catchment-scale response in the urban watercourse?

The results suggest that upstream tree planting and woody debris can have a modest impact on catchment flow response. Figure 9.3 gives an indication of how a 'max-NFM scenario' achieves diminishing reductions in peak magnitude as design storm severity increases. These interventions, which require transformative and extensive change in land management practices (as shown in Figures 5.1, 6.2 and 7.1) achieve maximum peak flow reductions, during a 10 year event, of 32%, 57% and 25% for the Bin Brook, Asker and Todmorden catchments respectively. Section 9.4 hypothesises that the differing effectiveness derive primarily from variations in (i) local topography and (ii) intervention extents.

The parametrisation and magnitude of NFM representation (although justified in section 3.8 and evaluated in sections 3.12.1.3 and 9.6.1) have been treated definitively. Given the nascent evidence base behind attenuation from physical interventions (discussed in section 2.2), this pragmatic methodological choice incorporates significant uncertainty. However, the consequent replication (see sensitivity analysis given in Figure 9.6) achieves modest reductions in line with previous modelling studies of similar interventions (Dixon et al., 2016).

Sub-Question 2: To what extent does inundation of outfalls by the receiving watercourse influence surface drainage response?

This sub-question was intended to clarify whether inundation of outfalls is a genuine issue and can be interpreted in two ways. Firstly, it invites scrutiny over the existence or frequency of outfall inundation. Secondly, it questions whether any such inundation could, in specific locations, have an adverse effect on drainage performance.

Existence and frequency of outfall inundation

The research began by conceptualising the 'rural-urban interface' in Figure 1.1 to help frame the subsequent evaluation of how responses from the rural and urban environments might interact. This figure suggests a broadening of the traditional domain within which the performance of urban drainage systems can be examined.

Section 2.3 evaluated the management of surface water in England and highlighted the often neglected issue of outfall inundation as well as other rural pressures on the urban system. In coastal scenarios, there is increasing awareness of how tidal locking of outfalls can exacerbate urban flood risk (Shen et al., 2019). In the UK, there have been a limited number of reported examples of river levels having a similar effect (Chen et al., 2010; Ellis and Viavattene, 2014). However, typical modelling exercises of surface drainage systems continue to assume a downstream boundary of infinitely free discharge from outfalls.

A key outcome from this research has been the questioning the validity of this assumption in certain circumstances. The results in all three case studies indicate that, as storm severity rises, outfalls become inundated by elevated river levels. Admittedly, case study catchments were selected based on anecdotal evidence for the existence of exacerbated outfalls.

However, all outfalls will have a 'threshold of inundation' (see Figure 2.6), which can vary significantly along a single reach – in the Todmorden case study this threshold was breached during a 10 year storm (Outfall 1) and a 50 year event (Outfall 2).

To demonstrate the applicability of the identified trends in the results, Figure 9.5 provides a normalised risk profile which can be applied to any urban watercourse to understand how upstream NFM may influence the inundation of outfalls.

Impact of inundation on drainage performance

The second way to interpret this sub-question is to investigate whether the existence of outfall inundation would adversely impact drainage performance.

In all three case studies, the surface volumes dispelled onto the surface during design events are largely minimal. For instance, despite both of Gough Way's outfalls being inundated during from the 10 year event, the 50 year event causes only $7.4m^3$ of surface flooding. This is nuisance flooding, with no serious risk to life or of significant property damage. Nonetheless, such volumes represent system failure and will have implicit costs (e.g. exacerbation of maintenance costs). Surface volumes are heavily influenced by the latent system storage – the same 100 year event in Todmorden causes $19.7m^3$ of flooding above Outfall 1, but none above Outfall 3. This is partly because of the longer and wider culvert lengths making up the latter's sub-system.

Alongside this, surface volumes are shown to be highly dependent on the synchronisation of outfall inundation and urban rainfall. As a result, observed rainfall typically causes much larger flood volumes (because the single, uniform pulse of the design rainfall causes minimal synchronicity). For instance, the hyetograph during the calibration period for the Todmorden model results in rainfall falling during high levels in the Calder, creating $45m^3$ of flooding above Outfall 1. The importance of this is further highlighted by the results given in section 8.3, which evaluates the role of different storm tracks in the Calder case study catchment. Total surface flooding (i.e. sum of all four Calder sub-systems) ranges from nothing to $12.6m^3$, depending on the downstream synchronicity.

In summary then, outfall inundation can make an impact on downstream drainage performance, although the magnitude of that impact will be dependent on the relative timings of the rural and urban rainfalls.

Sub-Question 3: How is drainage performance affected by moderation of levels in the receiving watercourse?

Having established impact from urban watercourses on the performance of contributing surface drainage, the study applied upstream NFM interventions to understand the influence of slowing the rural response. The two metrics used to understand consequent changes in outfall behaviour were (i) inundation duration and (ii) inundation delay.

In events that only just breach the inundation threshold, modest attenuation achieved by upstream NFM enables complete removal of outfall submersion. Examples of this include Asker and Todmorden's Outfall 1 during the 10 year event. However, as storm intensity increases, baseline inundation durations become prolonged and the attenuating impacts of

NFM decrease. This results in a broad diminishing of the reduction in inundation duration achieved by upstream NFM. Indeed, in all three catchments there are storm intensities where the marginal attenuation achieved by upstream NFM *prolongs* the time a downstream outfall is underwater. Figure 9.1 defines this as the ‘tipping point.’ Figure 5.5 offers a useful indication of how the greater the intervention, the more likely the risk of a tipping point being reached for downstream outfalls. However, there are two caveats to this. Firstly, the storm severity required to reach this point results in the emergence of fluvial flood risk (as Figure 9.4 shows). Secondly, this study has not considered the failure of in-channel woody debris interventions which, while potentially having other exacerbating effects, would further diminish NFM impact.

Despite this, across all three case studies and during the full range of design and calibration events, upstream NFM largely has a positive impact on drainage performance (only a few saw negligible effect). This is because the influence of upstream NFM on the *delay* of inundation is more consistent (as shown by Figure 9.2). The delay in inundation created by the upstream NFM allows greater volumes of water to escape through the outfall, thus increasing the effective capacity of the contributing system. As storm severity increases, although the NFM-induced delay becomes smaller, the absolute reductions in surface flooding become greater. This is because during these events more water is forced through the system before outfall submersion. For instance, in the Gough Way estate during the 50 year event, the max-NFM scenario reduces surface flooding by $7.4m^3$ but in the 100 year event this increases to $19.9m^3$.

Overall then, this research indicates that attenuation from NFM can consistently improve downstream drainage performance. This benefit relies on the urban response being much flashier, meaning that slowing of the rural hydrograph by upstream interventions desynchronises (if only marginally) the two responses. Therefore, this benefit is dependent on physical catchment characteristics and storm track (discussed as a subject for further study in section 8.3). This research has not scrutinised this benefit with different patterning of multiple events (as laid out in section 9.7.2) where the delay and prolongation of inundation may have detrimental impact.

Central Research Question: What effect can catchment-scale NFM interventions have on the performance of downstream urban surface drainage systems?

The results of this research have questioned the appropriateness, in certain locations, of assuming free discharge from surface drainage outfalls. Inundation of outfalls by local watercourses can lead to surcharging and sometimes failure (albeit largely nuisance flooding) of drainage systems.

Provided that outfalls are inundated by the watercourse during the baseline case, the modelling methodology suggests that attenuation of catchment response by NFM interventions (in this case tree planting and in-channel woody debris) can influence behaviour at downstream drainage outfalls.

Both the reduction and delay of the outfall inundation diminish with increased storm intensity. This would suggest that benefit from upstream natural interventions will be greatest in catchments with low-lying outfalls in the downstream urban watercourse. However, these outfalls are also more susceptible to reaching a 'tipping point' where attenuated rural hydrographs begin to prolong the inundation duration. Despite this, the continued (if slight) delay of the hydrograph means greater volumes pass through the outfall before inundation occurs, thereby increasing the effective capacity of the system and reducing flood volumes. At no outfall in any of the modelling across all of the case studies were there any negative impacts identified from upstream NFM (although section 9.7 highlights further work is needed to understand this phenomenon across multiple events).

In essence, promotion of free discharge from urban drainage by upstream NFM is dependent on complex interdependencies between (i) the local geometry of the outfall and receiving watercourse (ii) the severity of the storm event and (iii) the magnitude of the upstream intervention.

There is no suggestion of upstream NFM interventions providing a panacea for problems with downstream surface drainage performance – the limited benefit obtained has to be considered in the context of the substantial physical intervention required to replicate the max-NFM scenario. On the other hand, the results suggest that 'slowing the flow' upstream can offer benefits at multiple outfalls along an urban watercourse.

Better understanding of the many benefits accrued from NFM interventions will drive the physical implementation of projects (Lane, 2017). While the improvements to outfall discharge would not, in themselves, justify implementation, their potential to provide ancillary benefit (within a scheme focused on fluvial flood mitigation and/or water quality improvements) by contributing to a water level management strategy should not be overlooked.

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Appendix A

Exemplar Code

This appendix presents pieces of exemplar code used to couple Dynamic TOPMODEL and HEC-RAS (the rural component of the methodology justified in Chapter 3). It also gives a brief insight into script used for the HEC-RAS Controller in Matlab.

Both this coupling and the Controller are largely unrecognised techniques (but potentially extremely useful in many settings). This appendix is brief, annotated overview of the different modelling used during this research. It is intended as a useful guide for further, unrelated work in the future.

For more specific detail on the scripts used during this research please see the supplementary information given alongside the published work derived from this research (a list is given at the beginning of the thesis).

The first short script gives a generalised, simple run of Dynamic TOPMODEL in R. This takes spatial and temporal inputs to produce catchment flows.

```
##################################
#Example Dynamic TOPMODEL Run Script (with calibration data inputs)
#Charlie Ferguson (July 2020)
#For detailled quesions please contact crf35@cam.ac.uk

##################################
# Load Required R Packages
library("dynatopmodel")
library("raster")
library("zoo")

##################################
#Spatial Data
disc<-discretise(layers = layers,
cuts = c(atb=5),
area.thresh = 1/1000,
chans = build_chans(AskerDEM,AskerDRN),
burn.hrus = list(a=RiverReaches,NFMAreas))
```

```
#Where:
#layers - a stacked raster set consisting of (1) DEM, and (2) TWI
#cuts - cuts to distingish HRUs (in this case of the TWI and Thiessen Polygons)
#chans - built with Dynamic TOPMODEL R Package funcion (using DEM and river network)
#area.thresh - defining smallest possible HRU
#burn.hrus - burn in layers on top of the discretisation (the individual buffers around each river reach and the areas being targeted for NFM)

##################################
#Temporal Data
obs<-list(rain=RainfallData, pe=EvapotranspirationData, qobs=FlowData)
dt=0.25
qt0<-as.numeric(obs$qobs[1,]/1000)
#Where
#RainfallData - at xts object of the gauged rainfall data (with a column for each of the three gauges) (in mm/h)
#EvapotranspirationData - at xts object of the potential evapotranspiration data (in mm/h)
#FlowData - at xts object of the gauged output flow data (in mm/h)
#dt - time step (in hours)
#qt0 - initial flow (required for subsequent run function)

##################################
#Set up optional graphics windows
par<-get.disp.par(graphics.show=TRUE,graphics.interval=6,max.q=1.5,max.rain=15)

##################################
#Populate model with calibration data
groups<-disc$groups

groups$ln_t0<-5.1
groups$m<-0.0064
groups$srz_max<-0.11
groups$vof<-85
groups$td<-18
groups$srz0<-1
vchan<-1600
#where:
#groups - is the table informing the properties of all the HRUs
#$****  - are the Dynamic TOPMODEL parameters required

##################################
#Populate model with calibration data

run <-  run.dtm(groups=groups,
weights=disc$weights,
rain=obs$rain,
routing= build_routing_table(dem = dem, chans = chans), dt=dt, qt0=qt0, vchan=vchan, qobs = obs$qobs, pe=obs$pe, disp.par=par)
#where
#run.dtm - is a function available in the Dynamic TOPMODEL R package
#routing - a table used to apportion flows to the catchment outlet
```

Automation of the coupling betwee Dynamic TOPMODEL and HEC-RAS (see Figure 3.4) was one of the key advances made in this research. This was enabled by the following script.

It is written in VBA and forms a Macro in excel. Its purpose is to convert river reach HRU inputs (i.e. output from Dynamic TOPMODEL) in CSV format into DSS files (which is the input format required for HEC-RAS). This script uses specific cell references as it is drawn from an excel file given in the supplementary information of (Ferguson and Fenner, 2020c).

```
Sub Macro1OpenCSV()
'Macro for converting CSV files to DSS Files
'Charlie Ferguson July 2020

'Principal Workbook name
WorkbookName = "DynamicTOPMODEL_HECRAS_Macro_Event8_ExtendedALTERATION"

DSSExcel.pblnDisplayOpenStatus = False

'Activates the accompanying workbook
Workbooks(WorkbookName).Activate
'
For rep = 1 To 14   'This sets up a closed ‘for loop’ in VBA. This equates to total number of iterations used
Dim Input_file_name As String   'Defines variable as string
Input_file_name = Sheets("ImportSource").Range("B" & rep).Value   'Takes the input file name from a referenced cell in the active workbook

Workbooks.Open Filename:=Input_file_name    'Opens the input file

Range("C2:CZ6145").Copy 'Copies the contained flow data


'[Note at this point a intemediate stage converting data to desired units may be necessary]

Workbooks(WorkbookName).Activate  'Current worksheet changed back to principal workbook
Worksheets("Export").Range("C13").PasteSpecial xlPasteValues 'Paste data to correctly formatted export file (see example in DOI detailed above).

Worksheets("Export").Activate

'[Now switch to working with (freely-available) HEC DSSVue Excel Plugin to export this data into DSS format. This is done by calling two key underlying functions here (both are copied from the DSS Excel Module with slight modifications [not included here for brevity -- please see full workbook at DOI].
```

Having obtained the requisite input DSS files, the HEC-RAS Controller was used to run simulations in HEC-RAS.

It should be noted that the pre-processing occuring within the HEC-RAS GUI (e.g. definining of 2D domain, mesh, location of input and output boundaries). The following code gives an example of how the controller is used in HEC-RAS to run a single simulation. In reality, this can be set up within loops with contributing text files being altered in each case.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Example HEC-RAS Controller Run Script
%Charlie Ferguson July 2020
%For detailled quesions please contact crf35@cam.ac.uk

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%File Inputs
HECRASProject="[String of file location for HEC-RAS project file]";
h=actxserver('RAS505.HECRASCONTROLLER');
%where:
%h calls the COM object that is the controller

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Simulation Run
h.Project_Open(HECRASProject);
h.Plan_SetCurrent('Plan 01');
h.Compute_CurrentPlan(0,0);
while h.Compute_Complete==false
pause(1)
end
h.Project_Close()
%where
% h.Project_Open, h.Plan_SetCurrent, h.Compute_CurrentPlan(0,0) h.Project.Close() are
     attributes of the COM function
% 'Plan 1' is the name of the plan being run


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Extraction of output
HECRASResults="[string of file location for the .hdf file associated with the current
     plan]";
HECRASResultsInternal="[string finding block of flow crossing the downstream flow
    boundary data within the .hdf file]";
Flow=h5read(HECRASResults,HECRASResultsInternal);

%where
%h5read is a function for reading hdf files within matlab
%Flow is matrix containing flow output
```

Appendix B

Construction of Rating Curves

Section 3.10.3 discusses the calibration of the upstream rural models and the necessity of comparing observed flows with the simulation. In two of the case study catchments (the Bin Brook and the Calder), this requires converting gauged level data into flow data using a depth-discharge relationship.

To do this, the Manning's equation (Equation 3.13) was used to construct rating curves. The uncertainties associated with this are discussed in section 3.12.1.2. The two rating curves are given in Figures B.1 and B.2.

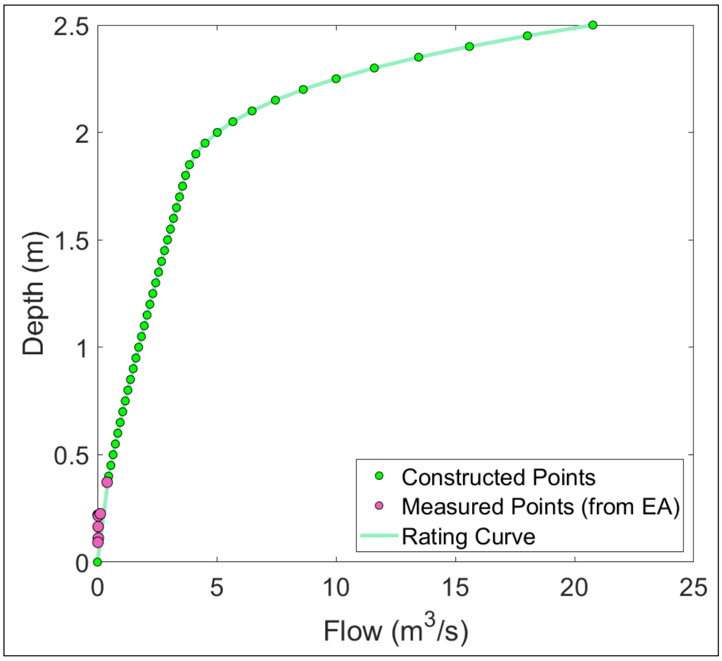

Figure B.1 Constructed rating curve for the Bin Brook case study (gauge shown in Figure 5.1)

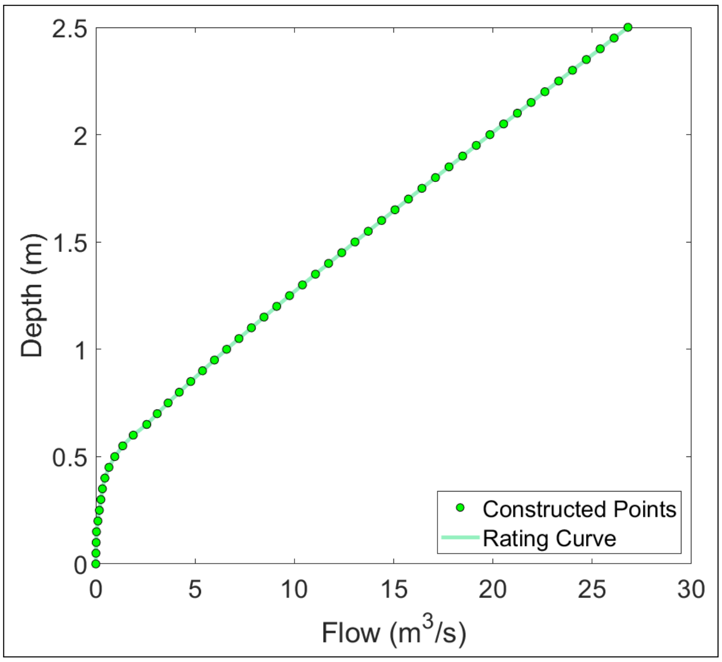

Figure B.2 Constructed rating curve for the Calder case study (gauge shown in Figure 7.1)

Appendix C

Uncertainty Frameworks

Bayesian approaches

There are many different approaches in the literature using Bayesian approaches in the calibration and uncertainty assessment for catchment-scale hydrological models (Jeremiah et al., 2011; Kavetski et al., 2018; Kuczera et al., 2010). The Bayesian Theorem is used to generate a 'posterior belief function', π, a multi-dimensional probability density function. A brief summary of the method will provided here. For a detailed discussion see Engeland and Gottschalk (2002). The posterior belief function can be expressed as (Jeremiah et al., 2011):

$$\pi(\theta|y) \propto p(y|\theta)p(\theta) \tag{C.1}$$

where $p(y|\theta)$ is the likelihood function and $p(\theta)$ is the prior distribution. The likelihood function provides the probability of replicating the observed data given a set of input parameter distributions. The 'prior distributions' of parameter inputs reflect the existing (and sometimes evolving) knowledge of the physical system. The non-linearity and dependence complexity of multiple parameters in distributed hydrological models means (π) can rarely be solved analytically (Jeremiah et al., 2011). Monte Carlo approaches are then used to generate a solution, which can often be computationally expensive. In many cases this limitation has been mitigated using the Markov Chain Monte Carlo method (MCMC) (Athira et al., 2016; Panday et al., 2014; Zhang et al., 2016). The MCMC sampling scheme involves iterative sampling within a plausible parameter domain. The posterior probability function is evaluated for successive parameter samples and pre-defined criteria are used so that the whole parameter set constantly produces improving results (Mara et al., 2016).

While Bayesian techniques provide traditional probabilistic confidence in a model parameter set, there are several drawbacks. First, informing the prior parameter distributions requires sufficient field data. The likelihood function can also be difficult to define (Engeland and Gottschalk, 2002). Techniques are also typically used only to quantify parameter uncertainty (Liu et al., 2017) and therefore need to be augmented by some consideration of model structure uncertainty. This is typically done by using multiple model structures to assess the same calibration. Examples of different techniques include Bayesian Model Averaging (BMA), the Multi Model Ensemble Method (MME) and the Framework for Understanding Structural Errors (FUSE) (Pechlivanidis et al., 2011).

Generalised Likelihood Uncertainty Estimation (GLUE)

The GLUE approach provides an alternative to these Bayesian techniques by rejecting the idea of an optimal solution and introducing the idea of equifinality (Beven, 2006; Beven and Binley, 2014). The concept of equifinality is based on accepting an imperfect knowledge of the physical system and that multiple sets of parameters, variables and parameters can, therefore, produce equally correct calibrations (Mirzaei et al., 2015). Jin et al. (2010) breaks down the GLUE methodology into: (1) a Monte Carlo approach, (2) definition of a likelihood function (3) calculation of likelihood values for each parameter set (4) rescaling of these values to create a cumulative distribution and (5) derivation of quantiles of uncertainty from the distribution.

A likelihood function defines the success of parameter sets in replicating the downstream observational data. The first component of the GLUE likelihood function is the definition of a threshold between behavioural and non-behavioural realisations. Realisations that do not meet this threshold (i.e. non-behavioural) are given a likelihood of 0 and not carried forward. As a result, GLUE can then be thought of as a rejectionist framework, which differs from more traditional Bayesian techniques (which typically just apply very low probability values). The likelihood function applied to the behavioural realisations must (i) be higher for 'better' simulations and (ii) scale with the relative belief in a hypothesis (rather than probability). Types of informal likelihood functions include:

1. applying a 'Limits of Acceptability' (LoA) approach across the whole realisation (e.g.Blazkova and Beven (2009); Liu et al. (2009); Westerberg et al. (2011);

2. comparing error between realisations and the observed hydrograph;

3. favouring parametric values (based on physical knowledge of the catchment) or realisations with particular phenomena (e.g. Metcalfe et al. (2017) favours simulations with minimal overland flow to reflect the presence of underground drainage).

The use of a 'less formal likelihood' is the primary difference between Bayesian interpretations of uncertainty and GLUE. The subjective nature of both the threshold and the function have been extensively discussed (Beven and Binley, 2014; Jin et al., 2010; Mirzaei et al., 2015; Montanari, 2005; Stedinger et al., 2008). The use of an informal likelihood function has been criticised by some as statistically incoherent, unreliable and generating different results to classical and Bayesian statistical methods (Stedinger et al., 2008). Despite this, GLUE remains popular for its conceptual simplicity and ease of implementation (Mirzaei et al., 2015). Beven and Binley (2014) also refutes the criticism, arguing that all uncertainty quantification exercises are subjective and that informal likelihoods reflect the belief of the modeller in the usefulness of a particular parameter set.

While the use of GLUE methodologies using informal likelihood functions are more frequent (Mirzaei et al., 2015), it should be noted that in special cases a formal Bayesian likelihood function can also be used Freer and Beven (1996).

While formal Bayesian approaches have been attempted to explicitly identify data, parameter and model structure error, Beven and Binley (2014) argue that without very strong information, epistemic uncertainty makes this unfeasible. Model structural error can also be considered implicitly within GLUE by applying the likelihood function to realisations generated using different models. This is much simpler than the ensemble techniques needed for Bayesian inference analysis.

It should be noted that the MCMC method (as referenced earlier in relation to Bayesian Inference) has also been used to mitigate computational expense during GLUE method (Blasone et al., 2008).