The potential for natural flood management to maintain free discharge at urban drainage outfalls

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Abstract
This study examines whether catchment-scale natural flood management (NFM) interventions could help to manage water levels in downstream urban watercourses and promote free discharge from surface drainage outfalls. A coupled modelling approach consisting of Dynamic TOPMODEL, HEC-RAS, and Infoworks ICM models is used to characterise the response from a small Cambridgeshire catchment. Four different NFM scenarios (consisting of in-channel woody debris and wider catchment afforestation) are defined. The attenuation of catchment response created by these measures is evaluated for an historic event and six different design storms. The consequent moderation of water depths at two downstream drainage outfalls is investigated with respect to maintaining free discharge from a surface drainage system. The case study results show that greatest reductions in the time of outfall inundation from NFM occur during frequent storm events (e.g., up to 5.75 hr during a 5-year event). These reductions diminish with increasing storm severity but, by slightly desynchronising rural and urban responses, upstream interventions continue to have modest benefit for downstream drainage performance (e.g., preventing system capacity being exceeded during a 100-year event). These results may interest water companies (increasingly involved in catchment-scale NFM projects) looking to improve performance of surface water drainage.

KEYWORDS
flood hazard, land management, natural flood management, surface drainage, water-level management

1 | INTRODUCTION

The term “natural flood management” (NFM) encompasses a range of interventions that promote (or restore) natural hydrological processes in the rural uplands of a catchment with the aim of manipulating stream discharge at certain locations (e.g., a given downstream reach) at certain times (e.g., at flood peak) (Iacob, Brown, & Rowan, 2017; Lane, 2017). This range can be categorised into interventions that (a) promote infiltration (b) reduce landscape connectivity and conveyance, or (c) create storage (Dadson et al., 2017). Examples include
woody debris in channels, moorland grip blocking, reduction of stocking densities, and reconnecting floodplains.

The evidence for catchment-scale NFM having an impact on preventing fluvial flooding in downstream, urban areas remains inconclusive (Iacob et al., 2017; McLean et al., 2013). However, three studies in the United Kingdom have amalgamated physical and numerical results at a range of spatial scales from many different catchments (Burgess-Gamble et al., 2017; Dadson et al., 2017; Forbes, Ball, & McLay, 2015). One of these, the Environment Agency’s (EA) “Working with Natural Processes (WwNP) – An Evidence Base,” also released nationwide opportunity mapping for afforestation and runoff attenuation features. Meanwhile, there has been growing awareness of the role NFM can play within a catchment-based approach to flood risk management (Norbury, Shaw, & Jones, 2018; Wingfield et al., 2019).

The wider benefits of NFM—including improvements to water quality, ecosystem services and biodiversity—have been evaluated in the literature (Collentine & Futter, 2016; Gilvear, Spray, & Casas-Mulet, 2013; Iacob, Rowan, Brown, & Ellis, 2014). This paper aims to examine an additional possible benefit by considering NFM as part of a water-level management strategy (rather than the traditional focus on prevention of fluvial flooding). NFM interventions, by mitigating water levels in downstream urban watercourses, could reduce the risk of drainage outfalls being inundated and thereby maintain the performance of nearby surface drainage systems.

Several factors make this an increasingly pertinent area of study. Firstly, with increased uncertainty in future rainfall predictions for much of the United Kingdom (Miller & Hutchins, 2017), there is likely to be greater stress on the conveyance capacity of urban drainage systems. This is coupled with increased development in British towns and cities and an aging surface water drainage infrastructure (much of which dates from the Victorian era) (Thorne, 2014).

Secondly, our changing climate will also impact water levels in receiving watercourses (Hannaford & Marsh, 2008; Stevens, Clarke, & Nicholls, 2016). For example, in South-East England, peak flows could more than double by 2070 (EA, 2016). The UK Climate Change Risk Assessment 2017 report states that in the “best case” 2°C scenario there will be potential for a general increase of between 5 and 20% in river flows during wet seasons (Committee on Climate Change, 2016). This will increase the likelihood of drowned outfalls (i.e., when river channel flow submerges a drainage outfall) and thereby the potential for surcharging in the drainage network.

A third factor is the impact of UK policy currently encouraging house building in high risk flood areas—over 11,000 new properties in England are to be constructed in these areas over the next 4 years (Halliday & Barritt, 2020). Surface drainage in these urbanised areas is often directed to the local watercourse. As a result, generating sufficient head difference between the outfall invert (i.e., the lowest point of the cross-section) and the maximum watercourse depth is increasingly constrained by physical geography.

## 2 | SURFACE WATER MANAGEMENT IN THE UNITED KINGDOM

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 & Davies, 2011). Flooding of such systems (i.e., “surface water flooding”) is caused by a variety of interacting mechanisms (Kázmierczak & Cavan, 2011). These can include pluvial flooding, snow melt, groundwater flooding, or local watercourse exceedance (Priest, Parker, Hurford, Walker, & Evans, 2011). There are currently 3.2 million UK properties currently at risk of surface water flooding (DEFRA, 2018).

One important part of the public policy approach to this risk can be traced to the seminal Pitt Review (Pitt, 2008) which was published in response to the UK 2007 floods (which caused estimated damages of over £4 billion). While controversally attributing two thirds of the 2007 Somerset level flooding to inadequacies in surface water drainage systems, it also provided the catalyst for the creation of Lead Local Flood Authorities and subsequent preparation of local flood risk management (LFRM) strategies (Ellis & Lundy, 2017). Two key components of LFRMs are (a) surface water management plans (SWMPs) and (b) catchment-based flood management plans (Benson & Lorenzonzi, 2017).

A SWMP provides a strategy for identifying and managing sources of surface water flooding (including sewers, drains, groundwater, surface runoff, and small watercourses) (DEFRA, 2010). A key component of SWMPs is to identify opportunities for sustainable drainage systems to mitigate risk through restoration of natural hydrological processes by creating temporary storage, filtering pollutants, and encouraging infiltration (Hoang & Fenner, 2015). The benefits of these source control techniques on surface water drainage have been widely discussed in academia (Alsubih, Arthur, Wright, & Allen, 2017; Hamel, Daly, & Fletcher, 2013; Pappalardo, la Rosa, Campisano, & la Greca, 2017) and resulted in an evolution of terms and philosophies in recent years (e.g., Water Sensitive Urban Design, Water Sensitive Cities.
Integrated Urban Water Management, etc.) (Fletcher et al., 2015).

However, in modelling exercises the urban drainage environment is typically considered as an isolated domain. The updated UK National Flood Map for Surface Water is a case in point. It forms the technical underpinning of many SWMPs but assumes free drainage from the outfall as a downstream boundary condition (EA, 2019). The limitations of this assumption have been recognised in DEFRA (2015).

Admittedly, in many cases the impact of flows crossing the rural–urban interface (see Figure 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).

There have also been several examples in the literature of the detrimental impact of inundated outfalls. For example, the Thames Estuary 2100 project, described by Ramsbottom, Tarrant, and Cooper (2006), highlighted the increase in flood risk from outfall flaps (used to prevent ingress into the drainage network) being closed more frequently by sea-level rise. There are also fluvial examples—Ellis and Viavattene (2014) report a flood risk in Birmingham (United Kingdom) being exacerbated by outfall flaps being closed because of high water levels in the nearby River Rea. Similarly, the restrictive impact of high water levels in local streams on the surface water network in the Kent town of Paddock Wood has been identified as a critical flooding mechanism (Jackson Hyder Consulting, 2015). 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 & Littlewood, 2011).

These examples of increased flood risk are partly the result of detrimental interactions between rural and urban surface water flows. The diagram in Figure 1 gives the surface flow network across the whole catchment-watershed, showing the nature of flows across the “rural–urban interface.”

This study focuses on channel flows crossing the rural–urban interface. Mitigation of rural surface runoff crossing into the urban environment (the other flow crossing the interface) is not within the scope of this research. Fluvial flooding—when capacity of a river channel is exceeded—is not included either.

3 | INTERACTION OF RURAL AND URBAN RESPONSES

There are four separate “flow states” in an urban watercourse with a flapped urban surface outfall (as shown in Figure 2). 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 factor considered here and State 2 occurs when an event causes the water level in the channel to reach the outfall invert. This depth is referred to as the “inundation threshold.” At this point,

**FIGURE 1** Catchment flows and the rural–urban interface (expanded from Rauch et al., 2002)
the outfall flap is assumed closed and preventing ingress of channel flow into the drainage network (i.e., a “drowned outfall”). If there is no discharge within the urban system (State 2a), no surcharging occurs. However, in State 2b (when the urban response is ongoing), surcharging does occur, causing a reduction in capacity of the surface drainage network.

The interaction of these rural and urban responses is dependent on (a) the hydrodynamic and geomorphological dispersion of the two contributing sub-catchments (b) the meteorological storm track and sequencing of the precipitation event(s), and (c) the geometrical characteristics of the receiving reach and contributing outfall.

The interaction of the two contributing flows to the downstream urban watercourse using their profiles and timings is shown in Figure 3. 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.

The inundation threshold is dependent on the local channel geometry and drainage outfall characteristics. With good design (i.e., significant head drop below the outfall exists even in high flow conditions) that threshold will not be reached. In the hypothetical case presented in Figure 3 the inundation threshold is exceeded, resulting in a “inundation duration.” The result is an example of flow State 2a (see Figure 2) because the urban outfall has already passed through the system—no surcharging of the urban system would occur.

However, there are several factors that could cause a more detrimental interaction. 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 surcharging in the drainage system. Another factor identified in the literature is the significant impact storm track can have on catchment response (Morin et al., 2006; Paschalis et al., 2014; Singh, 1997; Woods & Sivapalan, 1999). A particular storm track could result in a higher degree of synchronisation of the two responses. Finally, there is also the possibility of multiple events causing coincident responses and surcharging (discussed in the Flood Memory Project [Bhattacharya-Mis & Lamond, 2014]).

The study described here hypothesises that upstream NFM could play a role in minimising the duration of inundation, thus reducing the probability of surcharging and flooding of surface water sewers.

4 | INITIAL CASE STUDY

4.1 | Location

The case study catchment (~18 km²) is part of the Cam and Ely Ouse river basin in Cambridgeshire, United Kingdom. The river drains from an area west of Cambridge and passes through rural, intensely farmed land before entering the city and draining to a confluence with the Cam river (see Figure 4).

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. Arable agricultural land makes up ~80% of the catchment area. There are two small villages (Coton and Hardwick) in the uplands. The north end of the M11 motorway crosses the lowlands of the catchment.

Despite being a low-lying catchment in a dry area of the country (average annual rainfall between 2012 and 2017 was 590 mm), the impermeable geology means there is a significant downstream flood risk for a housing

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**Figure 2** Different flow states in an urban watercourse with a flapped surface drainage outfall

**Figure 3** Hypothetical example of flows creating State 2a (See Figure 2) in an urban watercourse
estate located on the fringes of Cambridge. An October 2001 event caused flooding to at least 28 homes with a depth up to 0.9 m (EA, 2013). At the time, it was estimated widespread property flooding would occur during a 1 in 25-year event (EA, 2007).

This risk is exacerbated by a culvert which transfers flows underneath the estate (see Figure 4). Despite the existence of a bypass channel, the under-sized culvert (1,500 mm diameter) causes a throttling effect for flows seen in a greater than a 1 in 5-year event (EA, 2003).

Critically (for the purposes of this study), the majority of surface drainage for the estate drains directly into this underground culvert (see Figure 4). The surface system has had several instances of surcharging and nuisance surface flooding reported by local residents.

4.2 | Interventions

There has been sustained local interest in implementing NFM within the case study catchment to improve water quality and reduce its flashy response (EA, 2003). This paper evaluates the impact from two forms of hypothetical intervention: (a) in-channel large woody debris (LWD) and (b) catchment-scale afforestation (at two different extents—see Figure 4). While in reality these
interventions would face significant barriers to implementation (including stakeholder resistance, location of sufficient funding, significant delay before maturity, etc.), they offer insight into the impact of wholesale change in the land-management practices across the catchment.

The modelled in-channel woody debris was applied at least 50 m from any infrastructure (e.g., bridges, buildings, or culverts, etc.). This was done to recognise the fears of potential damage from movement of such debris (Curran, 2010; Dixon & Sear, 2014). Such an intervention would require installation of artificial debris (as done by Addy & Wilkinson, 2016) and would cover 52% of the total channel length. In this study, the intervention is represented in a hydraulic model by increasing Manning’s roughness to 0.1 (following similar methods as in Thomas and Nisbet (2007), Odoni and Lane (2010), and Dixon, Sear, Odoni, Sykes, and Lane (2016)).

Two different extents of hypothetical afforestation were investigated (and are shown in Figure 4a). 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 (~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 United Kingdom and has planted over 125 acres with apple trees and wildflowers (Burgess, 2017; Newman, Pilbeam, & Briggs, 2017). The modelled tree planting intervention in this study was represented through parameter alterations of a hydrological model (discussed below). These alterations were derived from Hankin et al. (2016) and are shown in Table 1.

### 4.3 Available data

A Digital Terrain Model (DTM) with a spatial resolution of 1 m was obtained using OS Terrain data extracted from EDINA Digimap. A catchment watershed was then created using the SAGA GIS toolbox. The river network (shown in Figure 4) was obtained from the OS MasterMap Water Network. Evapotranspiration data was obtained from the Centre for Ecology and Hydrology’s (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 4) is located outside of the watershed in west Cambridge, but is at a similar elevation. This data was obtained in total mm fall across each 30 min time interval with an existing record going back to 2003. This was resampled to a 15 min interval to match the river gauge data.

There is a single river gauge on the catchment—see Figure 4. It is ~500 m upstream of the housing estate. Data requested from the EA contained water level data (with a 15 min time interval) with a record from 2008 to the present day. 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 (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.

### 4.4 Modelling methodology

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

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**Table 1** Calibrated parameters in dynamic TOPMODEL and tree planting scale factors

| Parameter                      | Description                                | Value   | Tree planting scale factor |
|--------------------------------|--------------------------------------------|---------|---------------------------|
| $\ln(T_0)$ (m²/ hr)           | Lateral saturated transmissivity           | 6.1     | $\times 1.5$ (to $T_0$)  |
| $m$ (m)                       | Form of exponential decline in conductivity| 0.007   | $\times 1.2$             |
| $srz_{\text{max}}$ (m)        | Maximum root storage                       | 0.25    | —                         |
| $srz_0$ (%)                   | Initial root storage                       | 0.98    | $\times 0.99$            |
| $t_d$ (hr/m)                  | Unsaturated zone time delay                | 36      | —                         |
| $v_{\text{of}}$ (m/hr)        | Overland flow routing velocity             | 45      | $\times 0.75$            |
| $v_{\text{chan}}$ (m/hr)      | Channel flow routing velocity              | 1,100   | —                         |
The rural response (i.e., upstream of the river level gauge) was characterised by coupling Dynamic TOPMODEL and HEC-RAS (similar to methodologies described in [Hankin et al., 2019; Ferguson & Fenner, 2020]). Dynamic TOPMODEL evolved from TOPMODEL, a long-established semi-distributed, and semi-conceptual hydrological model (Beven & Kirkby, 1979; Gayathri, Ganasri, & Dwarakish, 2015; Lane, Brookes, Kirkby, & Holden, 2004; Metcalfe, Beven, Hankin, & Lamb, 2018). It has been used in numerous studies of varying application (Freer, McMillan, McDonnell, & Beven, 2004; Page, Beven, Freer, & Neal, 2007; Younger, Freer, & Beven, 2009) including evaluating NFM (Hankin et al., 2016; Metcalfe, Beven, and Freer, 2015). The model discretises the catchment into Hydrological Response Units (HRUs), which are assumed to respond in a hydrologically similar manner. This study discretised the catchment by topographic wetness index. The efficient parameterisation of the model (along with its inherent assumptions) means the properties of each HRU are defined using only seven parameters (see Table 1 for a list and descriptions), further simplifying the underlying solver and shortening simulation times. Horizontal flux between HRUs is then computed using a weightings matrix, \( W \) (created using the M8 multiple flow direction algorithm) and the kinematic slope-hydraulic gradient approximation (from TOPMODEL). The routed horizontal fluxes provide the inputs for the channel zone.

The R package implementation of Dynamic TOPMODEL routes channel flows to the catchment outlet using a linear network width function and by assuming a fixed channel velocity. This study has instead routed channel flows using the 2D HEC-RAS solver. While improving the numerical replication of the highly engineered and dendritic channel network, this also allows representation of the in-channel woody debris intervention (see earlier Section 4.2 for details). The two models were coupled by “burning” HRUs into the TOPMODEL discretisation around each of the 28 river reaches. The fluxes through each were then extracted to give reach-by-reach inputs to the channel zone in the 2D HEC-RAS model. This replicates techniques followed in Hankin et al. (2019) and Ferguson and Fenner (2020). The freely available 2D HEC-RAS module (which solves the full shallow flow equations using a finite element method) routed these flows across the 1 m resolution DTM to the downstream river gauge (using the diffusive wave approximation). At two points (where the channel runs underneath the M11 motorway), the channel network had to be burnt into the DTM to ensure modelled flow pathways follow those in reality (an established technique which is discussed in [Getirana, Bonnet, & Martinez, 2009; Schwanghart, Groom, Kuhn, & Heckrath, 2013]).

To aid calibration, the coupled model was constructed to produce an output at the downstream river gauge. However, this point is ~500 m upstream of the housing estate. 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 4.

The output from the coupled HEC-RAS model becomes the upstream input for the 1D Infoworks model. 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 23.7 m³ (see Table 2). In the absence of any other available data, the model was deemed suitable for approximating the behaviour of the estate’s surface drainage.

### 4.5 Rural models calibration

The model was run with a 15-min time step from 00:15 on July 1, 2012 until 00:00 on September 4, 2012. This calibration length compares with other, similar studies (Metcalfe et al., 2017, 2018). Calibration of Dynamic TOPMODEL was achieved using a Monte Carlo approach, which consisted of 5,000 parameter sets (randomly sampled between the ranges given in Table 1). These ranges were informed by both the characteristics of the catchment and previously reported calibrations (Beven & Freer, 2001; Freer et al., 2004; Hankin...
et al., 2016; Metcalfe et al., 2015, 2017, 2018; Younger et al., 2009). The resultant simulations were evaluated based on their (a) Nash Sutcliffe Efficiency (NSE) (b) estimation of the peak flow magnitude. The values for the “best” parameter set are given in Table 1. This parameter set was then used to produce input for the HEC-RAS model. To calibrate the hydraulic model, the underlying Manning’s value was altered from 0.02 to 0.04 (at 0.001 increments). The best fitting simulation from the coupled model (with a global hydraulic roughness value of \( n = 0.023 \)) is compared with the observed flows in Figure 5.

The numerical simulation produces a reasonable approximation of the observed flow, with the NSE estimation being 0.83. The simulated response is slightly flashier with the peak arriving at 05:30 on July 14, 45 min (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 water works substantially contributes to flows. However, the biggest discrepancy in the calibration simulation is the fact it does not reflect the magnitude of the event on July 20. One possible explanation is that the rainfall gauge, being 1 km outside the watershed (see Figure 4), 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.

**FIGURE 5** Comparison of simulation from coupled (HEC-RAS and Dynamic TOPMODEL) model and the observed flows at the downstream river gauge from July 1, 2012 to September 4, 2012

5 | CASE STUDY RESULTS

5.1 | Impact of NFM on downstream flows

The calibrated model was used first to produce downstream hydrographs for (a) the July 2012 event and (b) 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: (a) LWD only, (b) tree planting Option 1 only, (c) tree planting Option 2 only, and (d) an “NFM-max scenario.” This “NFM-max” consists of both LWD and tree planting Option 2 being applied together in the upstream catchment.

Figure 6 illustrates how each of these four scenarios attenuates the rural response during the 2012 peak event and three different design events (the 5-, 20-, and 100-year storms).

Figure 6 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 min). This inconsistency could result from differing hyetograph shapes. During the calibration peak event, approximately one quarter of the total rainfall (12.2 mm) fell during the first half hour. This compares with the 1.2 mm (~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 have 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 min in a 5-year event). One potential factor behind this may be the catchment’s shallow topography. This makes the storage created by tree planting more impactful than any slowing of (already slow) overland flow. On the other hand, by representing LWD as an increase in roughness along a river reach, the model is not capturing the storage created by the throttling (and 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. Certainly, 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. It is worth noting though, that the interventions’ impact is heavily dependent on their numerical representation within the coupled model. The nascent physical evidence base behind NFM means that the parameterisation and non-statistical treatment of interventions such as tree planting

**FIGURE 6** Impact of large woody debris, tree planting Option 1 (45% afforestation), tree planting Option 2 (79% afforestation), and the “Max-NFM Scenario” (a combination of large woody debris and tree planting Option 2) on peak reduction (PR) and peak delay (PD) of the July 2012 and three design storm hydrographs. NFM, natural flood management
or in-channel debris creates uncertainty in the resultant downstream impact. However, given this paper focuses on the rural–urban interface and impact of interventions on downstream outfall inundation, this approach was deemed fit for purpose here.

5.2 Impact of NFM on downstream water levels

While attenuation of downstream flows has traditionally been the focus of many NFM studies, there are also consequent effects on water levels in downstream reaches. This study is concerned with how these levels influence the ability of two surface drainage outfalls to discharge directly into the culvert. The location and local geometry of these two outfalls is shown in Figure 4. The Infoworks ICM model was used to establish the time that water levels were high enough to drown the two outfalls. This study assumed that discharge from surface drainage was prevented when the culvert’s water level rose above the outfall’s invert. This assumption is conservative 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. However, given the complexity in modelling such behaviour, as well as the fact these periods are likely to be shorter than the model’s 15 min time step, this was deemed a reasonable assumption.

Figure 7 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 4).

There are several trends visible in Figure 7. 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 hr 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, influence of upstream interventions diminishes. Therefore, for a 30-year event Outfall 2 is inundated for 13 hr, but the max-NFM scenario only creates a reduction of 1 hr.

It also worth noting that the calibration peak, approximately a 15-year event, causes at least 15 hr 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 (thereby submerging outfalls). The limited attenuation of this event is one reason for the very modest reduction in inundation durations (up to 0.5 hr 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 7](image-url)
Figure 7 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 6), there is sufficient attenuation (from the tree planting Option 2 and max-NFM scenarios) to prolong the time outfalls are submerged by 0.5 hr. 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.

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 hr (see Figure 7), there is insufficient water trapped within the system to cause surcharging or flooding of any manhole. By submerging the outfalls for 8.75 hr, 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 2.

| Event      | Total flood volumes from the surface drainage system (m³) |
|------------|----------------------------------------------------------|
|            | Baseline | Woody debris only | Tree planting Option 1 | Tree planting Option 2 | Max-NFM scenario |
| Calibration | 23.7     | 10.7             | 21.6                  | 18.1                  | 8.0               |
| 20 years    | 2.2      | 0                | 0.1                   | 0                     | 0                 |
| 30 years    | 6.5      | 0                | 1.4                   | 0                     | 0                 |
| 50 years    | 7.4      | 0                | 6.4                   | 3.1                   | 0                 |
| 100 years   | 19.9     | 0.2              | 18.1                  | 12.9                  | 0                 |

Table 2 states 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. Conversely, during the calibration event, the extended rainfall continues to fall on an already surcharged drainage system and this exacerbates flooding volumes. Despite this, all four interventions reduce flooding—the max-NFM scenario reduces the total volume by 65%.

These reductions contrast with the results presented in Figure 7, where the scenarios are shown to have very little effect on the inundation durations during the calibration event. Taken together, Figure 7 and Table 2 illustrate the importance that desynchronising 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 3 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 this to a certain extent, the LWD 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 7).

6.1 | Limitations

While this study has identified indicative evidence of upstream interventions being able to improve performance of surface drainage in the estate, the sources of uncertainty in the methodology should be acknowledged. Paucity of local data has necessitated assumptions in the construction of Dynamic TOPMODEL and HECRAS models. These assumptions include the use of uniform rainfall, heterogeneous application of hydrological parameters, use of a global roughness value in the hydraulic model, and channel morphology being informed by a 1 m DTM. Uncertainty has also been incorporated through methodological choices such as the loose coupling between the two models which does not distinguish between groundwater and overland contributions (and assumed inputs averaged along individual river reaches). Alongside this, while results from the Infoworks model agree with anecdotal evidence of the 2012 event, there is no data with which to conduct a formal calibration.

But perhaps most significantly, the numerical replication of the NFM interventions has relied on definitive values from other studies. Such extrapolation, as well as the dependence set on the parameterisation of interventions within the constituent model structures, introduces significant scope for error on their downstream impact. However, given the scope of this paper is to examine the impact of attenuation—from any source—on downstream drainage performance, this was considered a pragmatic methodological choice.

7 | CONCLUSIONS

The results from the case study indicate that considering the “rural–urban” interface can enhance understanding of urban drainage response and offer potential in improving performance. Elevated river levels preventing discharge from outfalls have been shown to have detrimental impact on drainage performance in the housing estate. The ability of the NFM considered in this study to promote free discharge at these outfalls is dependent on complex interdependencies between (a) the local geometry of the outfall and receiving watercourse, (b) the severity of the storm event, and (c) the magnitude of the upstream intervention.

While the NFM interventions’ ability to mitigate downstream water levels below the “inundation threshold” (defined in Figure 3) 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 min using the max-NFM scenario, surface flood volumes during the 2012 event 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 it could be argued that interventions of the kind modelled here may help mitigate nuisance flooding.

It is recognised that the indicative benefit identified here relies on significant changes in the catchment’s land management practices. Further study could make interventions more feasible by incorporating more sophisticated opportunity mapping techniques which also incorporate landowner engagement (e.g., Lavers & Charlesworth, 2017). It is possible the creation of a catchment-wide implementation strategy could be extended to other forms of intervention (runoff attenuation features, floodplain storage, etc.) and these might produce a similar effect with less disruption to landowners. However, 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. These other benefits would typically refer to ecosystem, biodiversity, and water quality improvements. This paper has provided prima facie evidence that NFM could also improve the effectiveness of downstream surface drainage outfalls.

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DATA AVAILABILITY STATEMENT
The data supporting this paper is available at: https://doi.org/10.17863/CAM.49826

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ENDNOTES
1https://naturalprocesses.jbahosting.com/
2https://www.cl.cam.ac.uk/research/dtg/weather/
3https://CRAN.R-project.org/package=dynatopmodel
4https://www.hec.usace.army.mil/software/hec-ras/download.aspx

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