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Evaluating the effectiveness of catchment-scale approaches in mitigating urban surface water flooding

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Evaluating the effectiveness of catchment-scale approaches in mitigating urban surface water flooding

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Keywords: Natural Flood Management, surface water drainage, coupled modelling

Summary

The argument for Natural Flood Management in the UK has strengthened in recent years with increasing awareness of the potential benefits gained from upstream interventions (especially improvements in water quality, public amenities and biodiversity). This study aims to develop understanding of another potential benefit – interventions promoting free discharge at downstream urban drainage outfalls by moderating water levels in receiving watercourses.

A novel, coupled model (linking Dynamic TOPMODEL, HEC-RAS and Infoworks ICM) is calibrated for the Asker catchment in Dorset, England. This predominantly rural watershed drains to the town of Bridport, frequently submerging a surface drainage outfall in a nearby housing estate. Two forms of upstream, catchment-scale intervention (hillslope tree planting and in-channel large woody debris) are modelled to understand their impacts on the functioning of the drainage network during both the calibration period and a range of design storms.

The results indicate that interventions have greatest positive impact during frequent events. For example, during a storm with a 10% annual exceedance probability (AEP), upstream NFM could reduce outfall inundation by up to 3.75 hours and remove any surcharging of flow within the drainage system in Bridport. In more severe storms, the results suggest interventions could slightly prolong the time the outfall was submerged. However, by slowing the wider catchment's response during the 3.3% AEP storm, upstream interventions allow more water to escape the urban drainage system and reduce the maximum surface flooding extent within the housing estate by 35%.

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Introduction

This paper examines the possibility that a series of upstream, catchment-scale Natural Flood Management (NFM) interventions could improve the functionality of surface drainage networks. These networks typically drain an urban storm water catchment using a series of pipe inlets (e.g. road gullies) before conveying the water (under gravity) to outfalls which discharge into 'receiving watercourses' (Butler & Davies, 2011). Performance of such systems can be difficult to quantify, with unpredictable and flashy failure modes (Palla, Colli, Candela, Aronica, & Lanza, 2018; Wheater & Evans, 2009). It is hypothesised here that upstream NFM might be used to promote free drainage from frequently submerged outfalls, thereby improving the resilience of the contributing drainage network.

It has been generally accepted there will be increased variability in river flows as a result of climate change (Hannaford and Marsh, 2008; Prosdocimi, Kjeldsen and Svensson, 2014; Penning-Rowsell, 2015). It is estimated there will be a general increase of between 5 and 20% in river flows during wet seasons in south east England (Committee on Climate Change, 2016). To combat this uncertainty, a Catchment-Based Flood Management (CBFM) philosophy has emerged in recent years, which aims to use a series of spatially discrete interventions to evolve rural catchment uplands and reduce risk of downstream fluvial flooding (Lane, 2017). In certain catchments, this CBFM approach will also influence how the downstream receiving watercourse interacts with urban drainage.

The paper presents a modelling case study investigating the impact of a series of upstream, catchment-scale interventions on the ability to sustain/improve free discharge at a particular downstream outfall and thereby reduce surface flooding in a nearby housing estate.

Catchment-based Flood Management

The dominant component of CBFM strategies to date has been catchment-scale Natural Flood Management (NFM), with interventions aiming to 'slow the flow' in catchment uplands in order to mitigate fluvial flooding for particular downstream reaches (Dadson et al., 2017; Lane, 2017). The evidence for local NFM impacts influencing the catchment-scale response (>10km^2) remains inconclusive (Iacob, Brown, & Rowan, 2017; Lane & Milledge, 2013). However, there have been increasing numbers of community-led projects being implemented in recent years (Rouillard & Spray, 2017). Examples of interventions include moorland grip blocking, afforestation, buffer strips and floodplain reconnection. These interventions range between those that are purely 'natural' interventions and those that are traditionally 'engineered'. For instance, the EA's 'Working with Natural Processes' evidence base defines a 'continuum of options' ranging from 'natural recovery' through to 'hard engineering' (Burgess-Gamble et al., 2017). Similarly, Dadson *et al*. (2017) define NFM interventions as those that 'seek to restore or enhance catchment processes' while at the same time offering 'significant co-benefits'. The Scottish Environment Protection Agency (SEPA) also argues that NFM might be used to augment traditional solutions (i.e. by reducing wall height or prolonging design life) (Forbes, Ball, & McLay, 2015).

It is argued here that, in addition to mitigating fluvial flooding in extreme rainfall, this range of interventions could also improve the resiliency of urban surface water drainage during lesser events. By moderating water levels of urban watercourses, upstream interventions could reduce submersion of frequently drowned drainage outfalls. In doing so, NFM would promote free discharge from the urban system and thereby improve the effective capacity of the network. The detrimental impact of receiving watercourses submerging drainage outfalls has been recognised in the literature (Douglas, Kobold, Lawson, Pasche, & White, 2007; Ellis & Viavattene, 2014) and there have been several identified examples in the UK (Craven & Littlewood, 2011; Jackson Hyder Consulting, 2015; Ramsbottom, Tarrant, & Cooper, 2006).

The potential impact of NFM on this interface will now be evaluated using a modelling investigation. This will focus on a flood-prone surface outfall in the Dorset town of Bridport and interventions in the upstream Asker river catchment.

Methods

Case Study

The River Asker drains a 48km^2 area of western Dorset before passing through the town of Bridport (population of approximately 14,000) and then discharging into the English Channel. The eastern uplands of the catchment (254m above sea level) mark the beginning of chalk groups that stretch 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 the alluvium deposits in the lower river reaches. Over 95% of the bedrock is classified as having either 'high' or 'moderate' permeability by the British Geological Survey (BGS). The catchment is predominantly grassland (approximately 62% of total area) with significant pockets of arable (24%) and woodland (8%). There are several small villages scattered throughout the catchment.

The town of Bridport sits on the confluence of three rivers – the Asker, the Brit and the Simene. 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 & Mann, 1987). However, water levels in the River Asker has influenced surface flooding with drainage unable to cope with intense pluvial events. This is also indicated by the updated surface water risk map (UK Government, 2019) within the drainage zone indicated in Figure 1, 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.

Interventions

There are currently no physical NFM projects within the Asker catchment. A GIS-based desk study was used to identify opportunity areas for two separate forms of intervention across three separate upstream sub-catchments (these are shown in Figure 1). These sub-catchments have been called 'north', 'east' and 'south'.

The first intervention was hill-slope tree planting, which aims to increase infiltration rates, slow surface runoff and increase losses through evapotranspiration (Healey, Smith, Pagella, & Ford, 2016). Several physical studies have shown this to be effective at the 'hillslope scale' (Archer et al., 2013; Marshall et al., 2014) although at catchment scale physical studies have had mixed results (Stratford et al., 2017). The areas 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 the aforementioned physical studies). This planting was represented using alterations to Dynamic TOPMODEL parameters (following Hankin *et al.* (2016) and shown in Table 1).

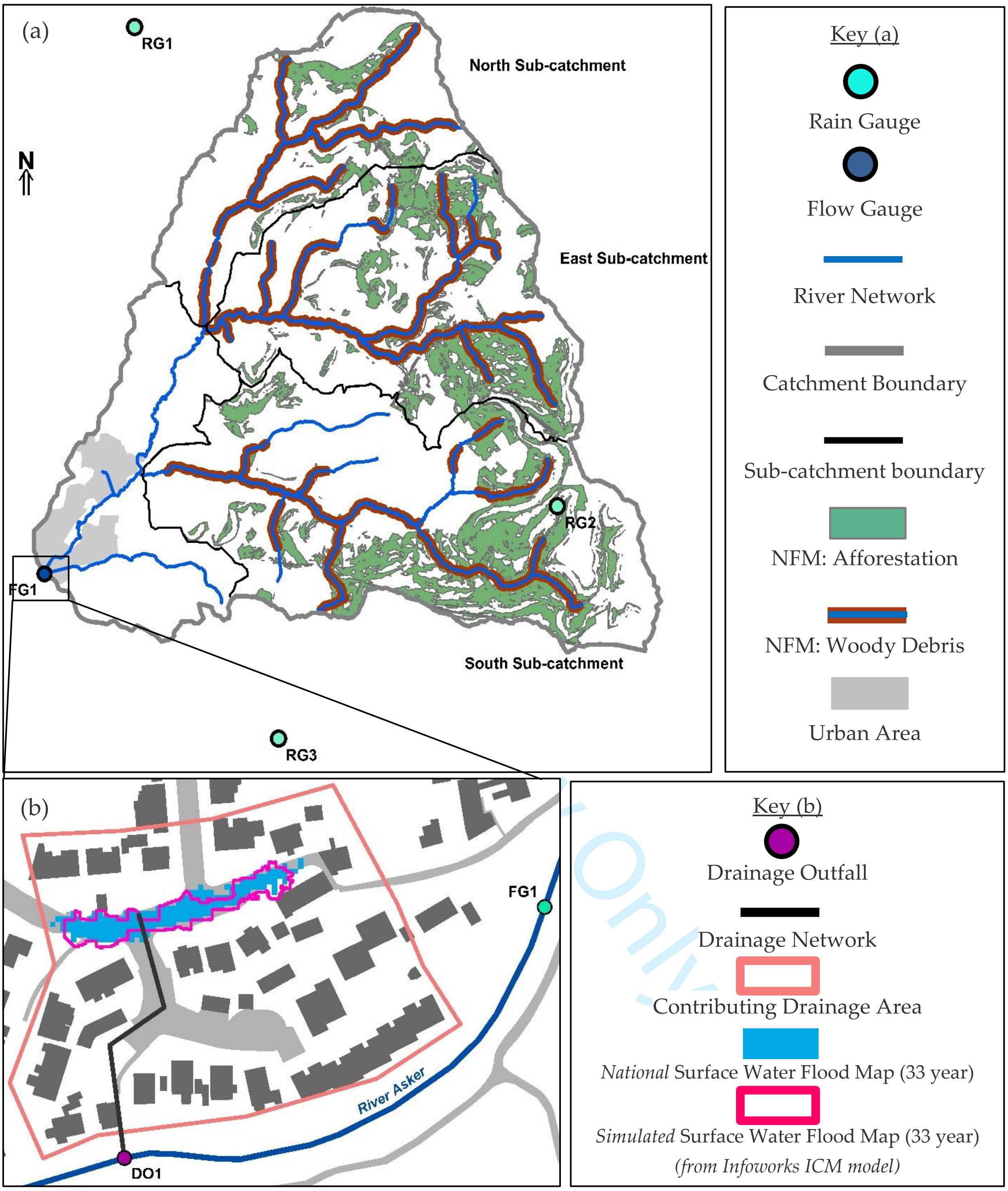

Figure 1: (a) Asker river catchment and (b) downstream Bridport surface drainage zone

The second intervention was in-channel woody debris, which aims to introduce storage through upstream ponding and slow channel flows sufficiently to have an alleviating impact in smaller events (Bornschein & Pohl, 2018). Several physical studies have reinforced this hypothesis (Norbury, Shaw, & Jones, 2018; Short, Clarke, Carnelli, Uttley, & Smith, 2019). The intervention was applied in areas of the channel 50m away from any infrastructure such as buildings or bridges (both upstream and downstream). This is to reflect the wider concern about moving debris blocking culverts and exacerbating flood risk (Curran, 2010; Dixon & Sear, 2014). The modelled intervention is located outside afforested areas, meaning the physical equivalent would require artificial placement of debris (as in Addy and Wilkinson (2016)). This intervention was represented in HEC-RAS by increasing the Manning's roughness coefficient to 0.1 (following other studies such as Thomas and Nisbet (2007), Odoni and Lane (2010) and Dixon *et al.* (2016).

Available Data

The Asker river is gauged downstream in Bridport (see Figure 1) with a Flat V Crump weir. The record (dating from March 1996 with a 15 minute time step) was obtained from the EA with a Freedom of Information (FOI) request. There is only one EA rain gauge in the catchment. However, two others were within 1.8km of the catchment (see Figure 1) 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.

A DEM (with resolution 5m) was created from OS Terrain data (extracted from EDINA Digimap) and used to delineate watersheds. EDINA Digimap was also used to obtain OS Topography and OS MasterMap Water Network for identifying infrastructure and the river network respectively. Land use data came from the CORINE Land Cover inventory (2012 – 2018 layer). The soils data was obtained from Cranfield University's LandIS portal.

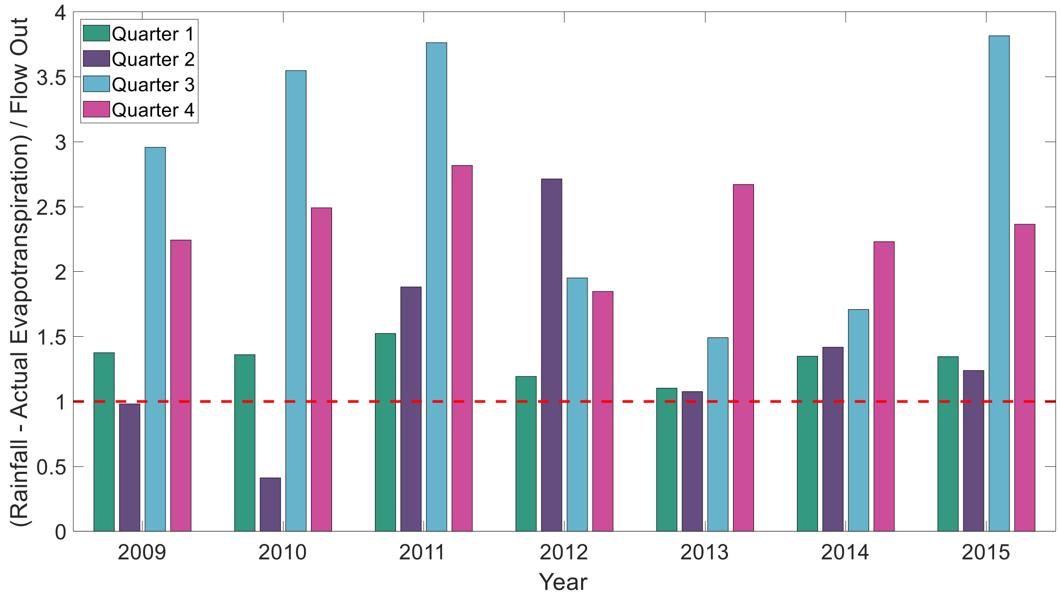

Figure 2: Mass ratio between rainfall input and flow output across a 10 year record

A preliminary mass balance check revealed significant and relatively consistent discrepancies in the measured data. Across the seven years shown in Figure 2, 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, Beven and Freer (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 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, Smith, & Pope, 2016)). Although less porous, infiltration into the lower sandstone bedrock (which covers 47% of total area) may also be causing groundwater losses. 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 means it has limitations for characterising the apparently complex sub-surface flows within this case study catchment. However, its beneficial characteristics (including effective parameterisation, reduced computing times, representation of NFM, coupling with downstream models) 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 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 rainfall input with a factor 0.74.

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 1). 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% 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. The model was then deemed as giving an acceptable estimation of drainage behaviour.

Calibration of Models

The response of the rural catchment (and subsequent implementation of NFM) was characterised by two coupled models: Dynamic TOPMODEL and HEC-RAS. The benefits of such a coupled approach have recently become recognised (Hankin, Metcalfe, Beven, & Chappell, 2019).

Dynamic TOPMODEL (a descendent of TOPMODEL) is an academically-established, semi-distributed, semi conceptual hydrological model (Beven, 1979). It is freely available as a CRAN package in the programming language R, the structure for which is discussed in detail in Metcalfe, Beven and Freer (2015). Dynamic TOPMODEL has been applied widely. It has been used to evaluate spatial variability of rainfall (Younger, Freer, & Beven, 2009), estimate contaminant transfer (Page, Beven, Freer, & Neal, 2007) and quantify impact of NFM (Hankin et al., 2016; Metcalfe, Beven, Hankin, & Lamb, 2017). By defining and then computing the response of areas that respond in a hydrologically similar manner, the solver can characterise catchment-wide response in a computationally efficient manner. The areas (termed Hydrological Response Units (HRUs)) are defined using seven main parameters (see Table 1). Conceptually, each HRU is formed of three storage volumes: root zone, unsaturated and excess, which fill and empty depending on the parameterisation and rainfall input. Flux between HRUs (i.e. subsurface and surface flow) is represented as transfer between these storage volumes and is computed using (i) a weightings matrix (from the M8 multiple flow algorithm) and (ii) the kinematic slope-hydraulic gradient approximation.

Parameter	**Description**	**Sampling Range**	**Final Value** (2 s.f.)	**NFM Impact** (see Table 1)
$\ln T_0$ $[\log m^2/hr]$	Lateral saturated transmissivity	[4 , 10]	9.3	× 1.3 (unlogged value)
m $[m]$	Exponential decline in conductivity	[0.001 , 0.015]	0.0036	× 1.2
srz_0 $[\%]$	Initial root zone storage	[0.1 , 0.3]	0.14	× 0.99
srz_{max} $[m]$	Maximum root zone storage	[0.98 , 1]	1.0	–
t_d $[hr/m]$	Unsaturated zone time delay	[10 , 60]	49	–
v_{of} $[m/hr]$	Overland flow routing velocity	[80 , 150]	92	× 0.75
v_{chan} $[m/hr]$	Channel routing velocity	[1000 , 2000]	1600	–

Table 1: Parameters and calibrated values in Dynamic TOPMODEL

The Asker catchment was discretised primarily by the topographic wetness index (TWI) – a ratio of the contributing area and slope for any point. This follows similar approaches in the literature (Hankin et al., 2017; Metcalfe, Beven, Hankin, & Lamb, 2018). Thiessen polygons, defined by the gauges shown in Figure 1, were also incorporated into the discretisation to better capture rainfall distribution.

A Monte Carlo procedure was used to calibrate the 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. The length of calibration period is comparable to other, event-based, Dynamic TOPMODEL calibrations for NFM (Metcalfe et al., 2017, 2018). The sampling bounds for 5000 parameter sets are given in Table 1. These bounds were informed by consideration of catchment characteristics and values used elsewhere in the literature (Beven & Freer, 2001; Freer, McMillan, McDonnell, & Beven, 2004; Metcalfe et al., 2018). The resultant simulations that achieved the peak flow within 10% were then ranked based on their replication of the inundation period (see Figure 3) and the Nash Sutcliffe Estimation. This parameter set was then carried forward to the HEC-RAS calibration.

In the CRAN implementation of Dynamic TOPMODEL, channel flow is routed to the catchment outlet using a 'time delay' histogram which is based on the geographical layout of the river network. This is computationally efficient and has been shown to offer reasonable approximation in small catchments (Beven, 1979). However, using HEC-RAS to route channel flow enabled evaluation of in-channel NFM interventions and consideration of sub-catchment synchronisation.

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) has established solvers for 1D, 2D and coupled 1D-2D scenarios (US Army Corps of Engineers, 2016). The full 2D shallow flow equations were solved (using HEC-RAS's implicit finite volume solver) to characterise flow across the catchment's DEM. Although this may be computationally less efficient, the 2D model was much easier to couple with Dynamic TOPMODEL and avoided the need for surveyed data of upstream river reaches. Also, in such a dendritic river network, a 1D model for the whole catchment would have been large and cumbersome (a similar argument is found in (Liu & Merwade, 2018)).

The two models were coupled by creating a 20m buffer around each of the 44 river reaches to act as HRUs. The input flows crossing into each of these (obtained from the Dynamic TOPMODEL solver) were then taken as individual reach inputs for the HEC-RAS model. The HEC-RAS Controller (a local API enabling automation of HEC-RAS modules) was used in a sensitivity analysis of a uniform channel roughness to calibrate the model. Manning's roughness coefficients between 0.02 and 0.04 (at a 0.001 increment) were trialled. The final value was 0.024, which gave a NSE value of 0.83 when comparing the HEC-RAS output flows with the observed (above 0.8 is deemed satisfactory in such models (Buytaert & Beven, 2009)). Figure 3 compares the final simulation with those observed at the downstream flow gauge (labelled FG1 in Figure 1).

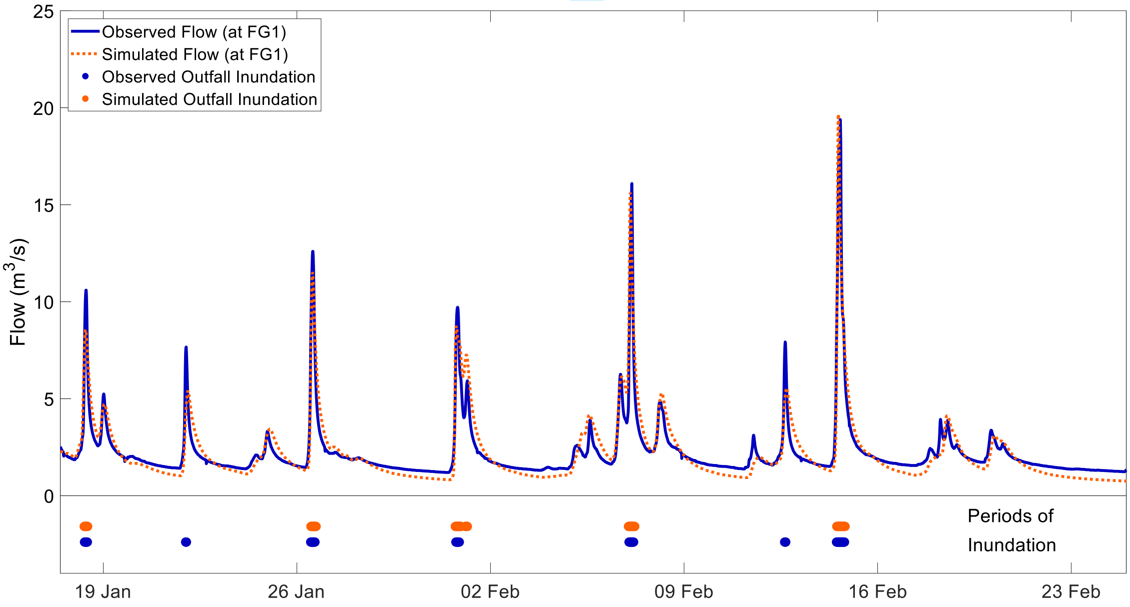

Figure 3: Calibration of coupled Dynamic TOPMODEL and HEC-RAS response

Although the coupled model has captured the maximum flow, across the calibration period the peak magnitudes are generally under-predicted slightly. While the flashiness of these larger events has been mostly replicated, the simulated response is more sluggish for smaller events. Although the base flow is under-predicted, the model has captured the timing of simulated events. Given the purposes of this study, this was critical and this simulation was deemed an acceptable fit.

Both upstream 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 1). 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 3). 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.

Results

This study investigated the impact of interventions when applied across three upstream sub-catchments (see Figure 1 for their delineation). There are seven different combinations of intervention – three when applied in a single sub-catchment, three with two sub-catchments and another when all upstream areas are altered. These were all run through the upstream coupled model.

Figure 4 shows the impact of these different combinations of intervention on the three of the largest flow peaks within the calibration 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.

Figure 4 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.

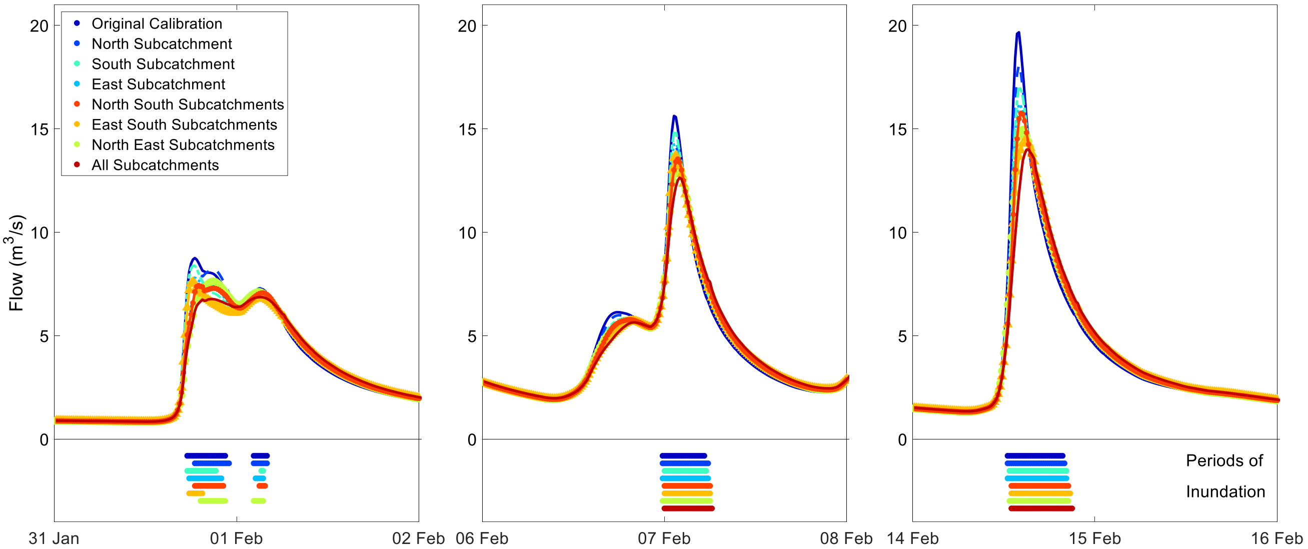

Figure 4: Impact of NFM on peak flows within the calibration

A series of seven design storms (all of which cause downstream outfall inundation) were also generated using FEH catchment descriptors and run through the coupled model. This was done in order to gain a better understanding of the impact of NFM on this catchment across a wider range of storms. Figure 5a compares peak reductions to changes in inundation duration for five 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).

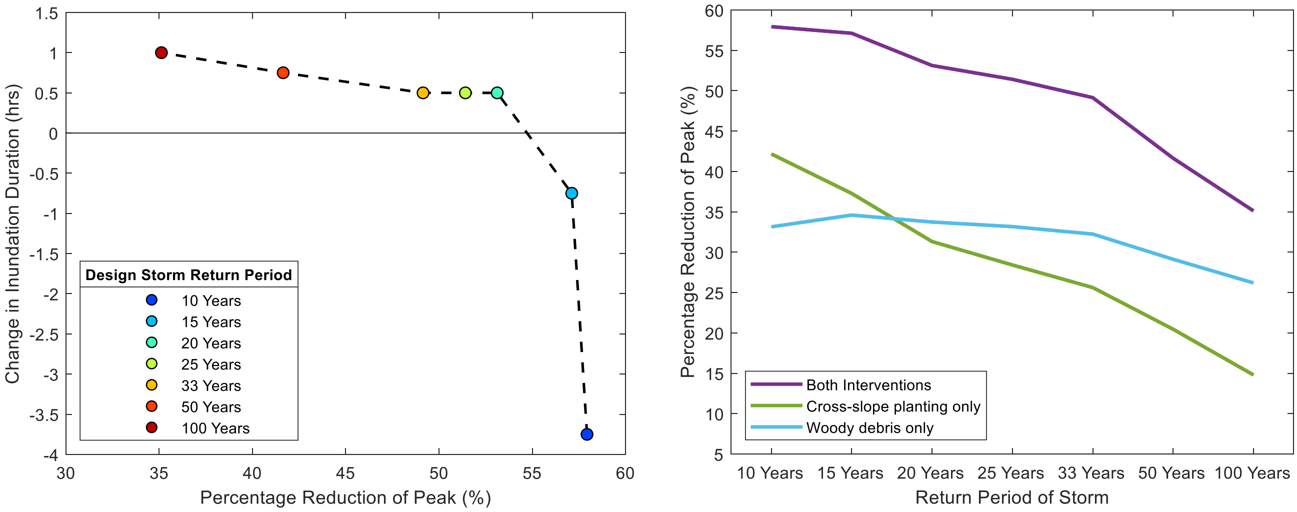

Figure 5: (a) Impact of design storms on downstream hydrograph and (b) individual contribution of different NFM types

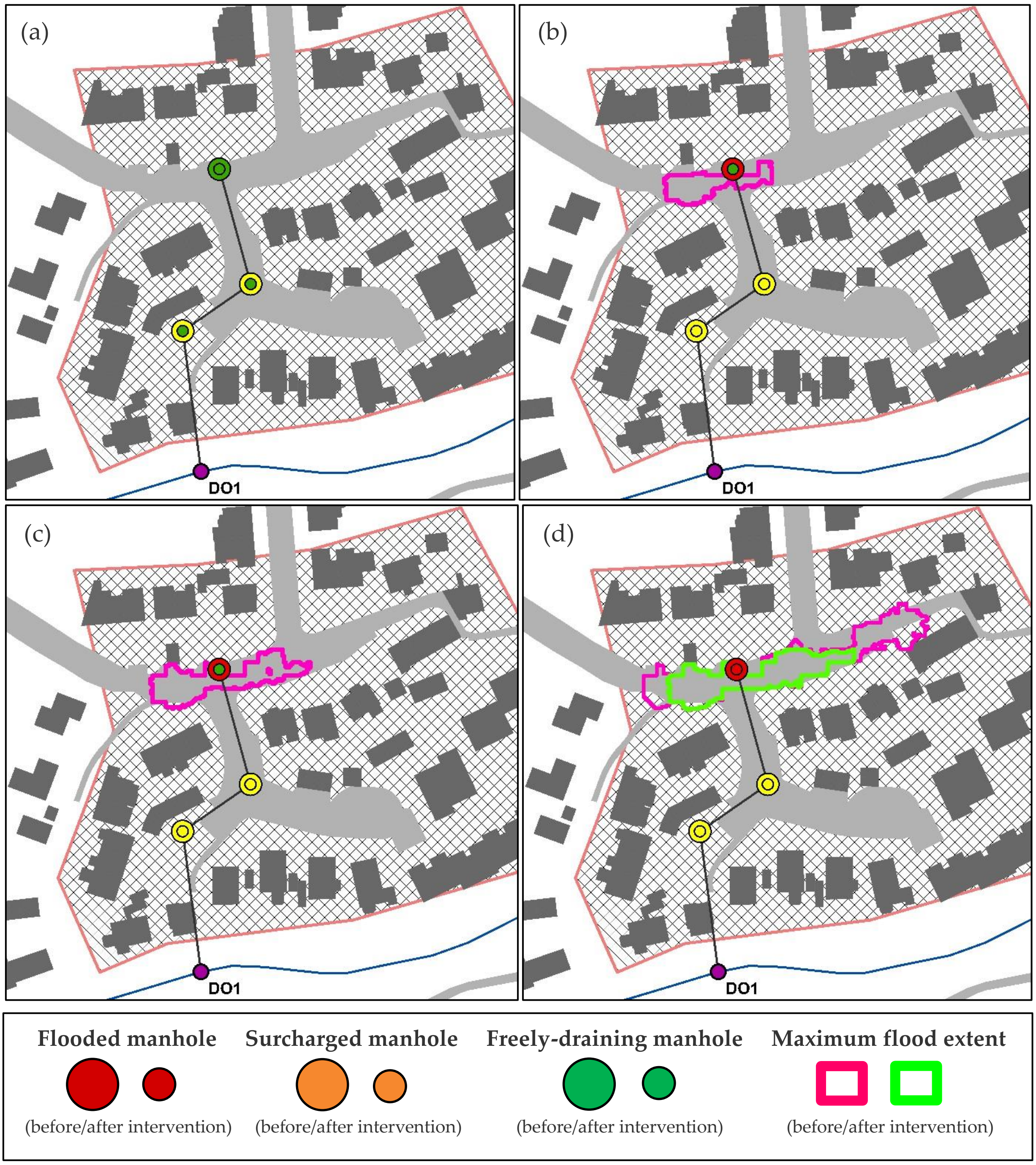

Figure 6: Functionality of Bridport surface drainage before and after upstream NFM interventions during a (a) 1 in 10 year storm; (b) 1 in 15 year storm; (c) 1 in 20 year storm; (d) 1 in 33 year storm

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 5b 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.

Figure 6 demonstrates the 'before' and 'after' states of manholes in the Infoworks ICM model to demonstrate 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 5a 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.

Discussion

NFM interventions are broadly successful in reducing the magnitude of peak flows in the River Asker during the calibration period (Figure 4). 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 Figures 5a). 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 relative 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, Lane, Hardy, & Reaney, 2014). However, in this case, there was no strong correlation between upstream interventions desynchronising tributaries and subsequent greater downstream reductions.

Figure 5b 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 5b 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 upstream interventions may be reducing the attenuating impacts of those lower in the hydrological system.

The results in Figure 6 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 & 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). It could also be argued that, although interventions are having a positive impact on a single storm, by prolonging the outfall being drowned the 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 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.

All of these findings must be tempered by significant sources of error in the modelling. Uncertainty in distributed hydrological modelling generally have been extensively discussed in the literature (Beven et al., 2015; Jeremiah, Sisson, Marshall, Mehrotra, & Sharma, 2011; Montanari & Di Baldassarre, 2013; Refsgaard & Storm, 1996). In addition, although the calibration procedure produced a reasonable fit with observed flows and has academic precedent, it is a highly idealised approach. Another significant source of uncertainty comes from the fact the evidence behind the impact of physical NFM remains inconclusive. Any numerical replication of intervention impact is therefore subject to significant error (in terms of both magnitude and parameterisation). Although representation of the interventions used in this study has been informed by the literature (see Table 1), extrapolation of their impact within the Asker catchment introduces further uncertainty.

Further study would benefit from sensitivity analyses of these numerical permutations to improve confidence in their downstream impact. Another source of error is the loose-coupling mechanisms between the three constituent models: Dynamic TOPMODEL, HEC-RAS and Infoworks ICM., which prevents any feedback between systems. Inputs into the river channel model from the hydrological model are independent of the level in the receiving watercourse. The 2D HEC-RAS model itself has been based on a 5m DEM (in the absence of sufficient river section data) and while this has enabled representation of woody debris across the catchment, the methodology would be improved with better representation of channel geometries. Also, any backwater effects across the downstream flow gauge (i.e. drowning of the weir) are not represented within the model.

Conclusions

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 resiliency of the urban surface water system. However, in larger events (e.g. beyond a 30 year return period), 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 the 'Available Data' section). 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.

In practice, stakeholder engagement is critical for any NFM implementation project (Howgate & Kenyon, 2009; Lavers & Charlesworth, 2017; Short et al., 2019). Although the interventions evaluated here would require wholescale changes in the management of the Asker River catchment, they demonstrate the impact available from an 'NFM max'. By expanding stakeholder understanding of flood risk sources, one can increase engagement in potential flood mitigation measures (Rust & Venn, 2018). This paper aims to widen stakeholder engagement in new direction by indicatively demonstrating the ability of selected upstream, natural interventions to improve resiliency within downstream surface drainage systems.

Further research with this methodology could take many different directions. A potential area of interest would be diversifying the interventions evaluated (e.g. on-line ponds, runoff attention features, hedgerow planting) to better understand better how they interact and complement each other within a CBFM approach. Another would be consideration of the desynchronisation of urban and rural responses under a variety of storm tracks, which could also provide further evidence of the benefits of catchment-scale interventions.

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.

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