Rapid surface water intervention performance comparison for urban planning

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ABSTRACT

Surface water flooding can be a significant source of damage and disruption in urban areas. The complexity of urban surfaces, the need for spatially disaggregated approaches and the multiplicity of interventions makes management challenging from a number of perspectives. This research responds to the challenge of selecting appropriate surface water management interventions by applying a fast assessment framework to generate evidence for comparing strategies at low resource cost during initial design. This is demonstrated by simulating flood dynamics and comparing damage costs in 144 flood scenarios. The main finding of this work is that a high-level quantitative assessment of large numbers of scenarios is capable of providing evidence to identify performance trends and consider resilience to extreme events at an early stage of planning.

Key words | decision support, green infrastructure, intervention performance comparison, resilience assessment, surface water flood management, sustainable drainage

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INTRODUCTION

Frequent and extensive damage caused by surface water flooding has changed perceptions about sources of flood risk, challenging a paradigm focused on fluvial and coastal flooding and affirming the need to invest in new frameworks and strategies to manage the consequences of excess surface water (Pitt 2008; DEFRA & Environment Agency 2011). In particular, uptake of new and innovative management strategies has been recommended (House of Commons 2016). An enhanced focus on surface water management is particularly relevant given the changes to climate, land use and demographics which are likely to exacerbate future flooding (Chocat *et al.* 2007; IPCC 2014). However, recent government reports indicate that surface water flooding is not being adequately managed, and presents a gap in flood management (Committee on Climate Change 2015). This is despite legal requirements for local flood risk management strategies to be developed and implemented, as set out in the Flood and Water Management Act 2010 (HM Government 2010).

An extensive range of surface water flooding interventions is available, including sewers, catchment management, sustainable drainage systems (SuDS), green infrastructure, designing for exceedance (DfE), property level protection (PLP) and resilience measures (Butler & Davies 2011; Fletcher *et al.* 2015; Woods Ballard *et al.* 2015). However, evidence for selection of techniques is limited by a technically demanding and resource-intensive option-assessment process (Elliott & Trowsdale 2007; Emanuelsson *et al.* 2014). Flood depths and damage costs associated with intervention performance are typically estimated using computationally expensive hydro-dynamic models, where the time taken to set up and analyse results is prohibitive of quantitative performance analysis for large numbers of scenarios. Other techniques such as multi-criteria decision making, geographic information system (GIS) analysis and expert judgement attempt to overcome this using simpler qualitative or proxy measures of performance, but these lack the detail required to robustly measure nuances of intervention placement. These constraints lead to a lack of evidence for decision support in the formative early stage of design and stifle innovative new management interventions.

Contemporary scientific and government literature also highlights the advantages of incorporating resilience within flood management (Ofwat 2012; HM Government 2016). Exploring the resilience of interventions requires analysis of extreme events beyond standard design conditions and requires many simulations (Mugume *et al.* 2015; Butler *et al.* 2016). Slow processing times associated

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with traditional 2D analysis techniques prohibit this, so new fast simulation approaches are required.

This study addresses the challenges of selecting interventions for surface water management by applying an initial assessment framework designed to enhance the evidence available for decision support. Rapid analysis is achieved using a recently published framework (Webber *et al.* 2018) that was developed to include a more detailed representation of interventions. The advantages of this approach mean that many simulations can be analysed quantitatively and quickly, so selection is evidenced by performance across a much wider range of rainfall events than is typically considered. The paper is structured by first using the approach to identify catchment flood dynamics and then examining intervention performance across a range of rainfall intensities and durations. Outputs from this approach are intended to refine the selection of events and interventions considered for detailed modelling.

METHODS

A fast assessment framework is applied to represent the study area, interventions, surface water runoff and damage costs (Webber *et al.* 2018). Analysis speed is achieved through use of easily accessible input data, a simplified representation of interventions and an efficient and innovative cellular automata (CA) based flood routing model. Previous research demonstrates the accuracy of the underlying CA flood model (Gibson *et al.* 2016) and its application across large zones in a catchment (Webber *et al.* 2018). This study advances knowledge by developing application towards a practical flood assessment through analysis of critical storm duration and exploration of the utility of screening defined interventions applied at a property scale.

A case study of a UK urban catchment is used to illustrate the advantages of the framework (Figure 1). Analysis is split into two stages, firstly assessing critical storm duration and secondly examining the effect of intervention performance over multiple return periods.

All data sources were intended to be easily accessible to respond to a challenge of early initial screening of catchments. Characterisation of the study area was undertaken using high-resolution 1 m LiDAR data to represent surface elevation. Building locations were identified using a shapefile and included in the simulation through a 0.15 m surface elevation uplift to represent the threshold level.

Land use was specified using online mapping. The effects of interventions and land use types were included through manipulation of the parameters in each cell which specified water input, output and runoff speed (Figure 2). An infiltration rate and roughness value was assigned to each cell based on the online mapping. Infiltration rates were specified in mm/hour based on catchment soil types (Bettess 1996; FAO 2016; Landis 2016). Roughness values were specified using commonly accepted Manning's n coefficients found in literature (USGS 1989; Butler & Davies 2011; Woods Ballard *et al.* 2015). The underlying drainage system was represented using a constant infiltration rate of 12 mm/hour as specified in the Environment Agency

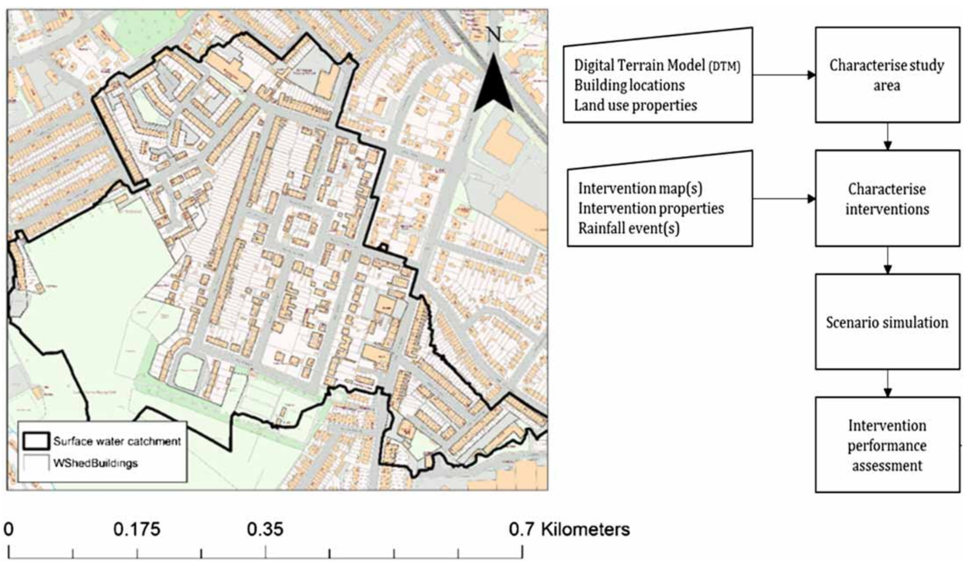

Figure 1 | Study catchment (left) and intervention performance assessment framework (right).

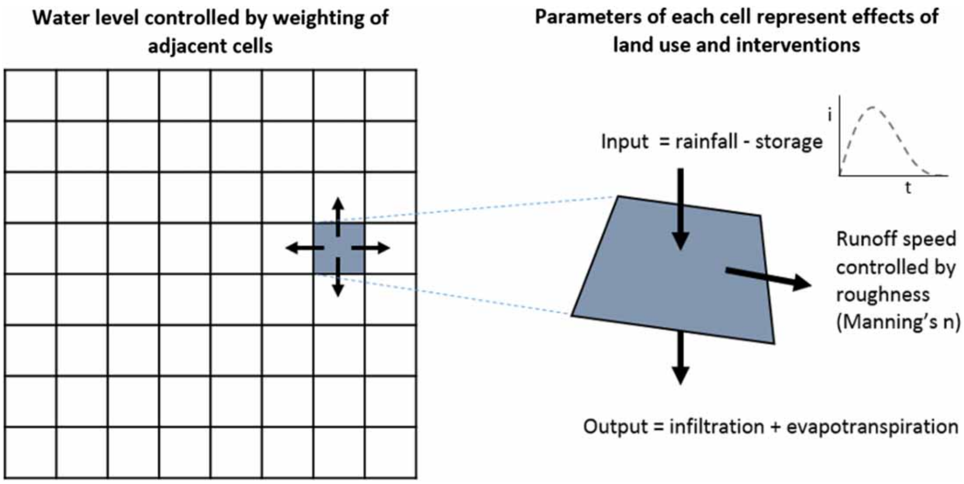

Figure 2 | Runoff modelling scheme and representation of interventions and land use in CADDIES.

methodology for high-level surface water mapping (Environment Agency 2013). It should be recognised that representing drainage systems using this approach is only suitable for the initial assessment of catchments, due to limitations associated with the simplification of underlying hydraulic processes (Webber *et al.* 2018).

Interventions which capture rainfall, such as rainwater harvesting, are represented through removal of input rainfall. Techniques which remove water from the land surface, such as sewers, infiltration features and subsurface drainage, are represented through increasing the water removal (output) from each cell. Interventions affecting surface roughness, either through changing the medium (i.e. concrete to grass) or through attempting to hold water (i.e. a swale) are represented through changing the roughness coefficient to alter runoff speed in each cell. Intervention scenarios were created as separate input matrices and overlain onto the study area matrices before simulation. This simple representation of intervention scenarios enables an efficient and easy-to-automate construction of scenarios.

Interventions were applied across all suitable surfaces in the catchment and included a do nothing baseline, installation of water butts (100 L), green roofs, permeable paving, rainwater re-use (1,500 L) and surface drainage upgrades. Intervention effects were based on previous studies and averaged to be applied on a cell scale (1 m^2) (Table 1).

Conservative intervention capacity values have been applied where the literature presents a range of capacities. This may limit the observed flood reduction of strategies. Water butt and rainwater re-use tank capacities were based on commercially available designs and academic literature (Woods Ballard *et al.* 2015). Green roof capacity

Table 1 | Intervention strategy effects per cell

Intervention	Rainfall capture (mm)	Infiltration rate (mm/hour)	Cell roughness (Manning's n)
Do nothing	No effect	No effect	No effect
Water butt	2.2	No effect	No effect
Rainwater re-use	15	No effect	No effect
Green roof	33	No effect	No effect
Permeable paving	No effect	17	0.015
Surface drainage	No effect	24	No effect

was based on recent published studies (Paudel 2009; Stovin *et al.* 2012). Permeable paving infiltration rates and surface roughness was based on a concrete block design and included additional uplifts for underlying soil characteristics and drainage system capacity (Pratt *et al.* 2002; Zachary Bean *et al.* 2007; Collins *et al.* 2008). Drainage upgrade rates were included through doubling the Environment Agency (2013) standard rate applied for broad-scale surface water modelling. Simplification of assumptions will provide a faster setup and analysis time but less accurate results, which should be applied as part of a screening process, prior to detailed design.

Surface water flood simulation was carried out using a CA based model, cellular automata dual drainage simulation (CADDIES), and a GIS-based hazard impact assessment tool (Figure 2; Guidolin *et al.* 2016). CA are regular grid-based processing environments which rely on simplified transition rules to simulate information exchange between cells. CADDIES applies this mechanism to 2D water routing using a Manning's equation to route runoff between cells based on water balance, elevation and roughness parameters. This approach was selected as the basis of an intervention assessment as it has the advantage of faster simulation times versus industry-standard hydrodynamic and Saint-Venant-equation-based models while achieving a similar level of accuracy. The processing requirements using CADDIES are reduced by five to twenty times versus other 2D simulation software whilst maintaining comparable accuracy (Gibson *et al.* 2016). Other simplified modelling approaches provide an increase in speed, but sacrifice simulating flood dynamics at a comparable scale and instead rely on GIS analysis or stakeholder evaluation of options (Weng 2001; Ellis *et al.* 2004; Martin *et al.* 2007; Makropoulos *et al.* 2007; Makropoulos *et al.* 2008; Young *et al.* 2010; Ellis & Viavattene 2013). This responds to the needs of decision support to provide an approach capable of screening the extensive range of potential interventions available.

Catchment rainfall was simulated using 1, 2, 3, 4, 6, 12, 24 and 48-hour design rainfall events. Design storms represented a constant rainfall intensity during 30, 100 and 200-year return periods (CEH 1999). Runoff duration extended five hours beyond the event to allow ponding. In total 144 simulations were run.

Damage cost was calculated by applying a flood damage curve to peak flood depths within each building (Hammond *et al.* 2016). For example, using Figure 3, damage to a building inundated to a level of 1.2 m would cost approximately 660 GBP/m^2. Total damage costs per scenario were calculated by adding the costs of all corresponding buildings. Costs were industry-standard figures for a three-bedroom semi-detached property, converted into an estimated cost per m^2 using average household sizes in England (Penning-Orwsell *et al.* 2010; DCLG 2015).

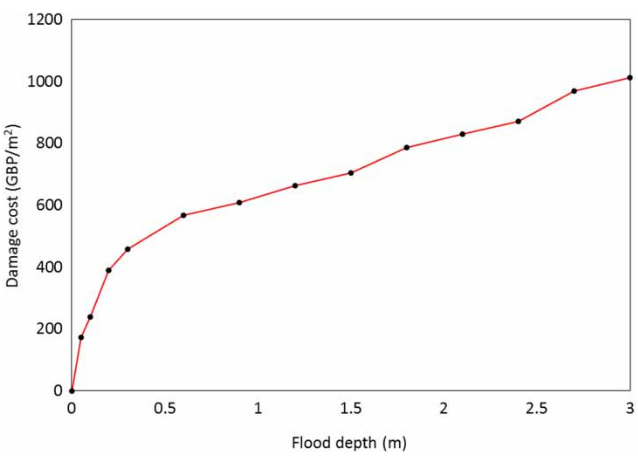

Figure 3 | Flood depth damage curve for a typical three-bedroom semi-detached property (Penning-Orswell *et al.* 2010).

RESULTS AND DISCUSSION

Identifying the critical storm

Figure 4 shows the total damage costs of design rainfall across 144 simulations, including all event return periods, durations and intervention strategies. The highest damage costs tended to occur during low-probability rainfall magnitude, with the highest cost at each duration associated with the 200-year event. Some crossover is visible, where certain strategies lead to higher damage costs at lower-probability events. A larger variation between damage costs was evident during shorter, higher-intensity storms. This merits further analysis and is discussed later in the paper in relation to the effectiveness of intervention strategies.

The highest damage costs occurred during the one-hour event. A clear trend is visible where higher damage correlates with shorter duration and more intense rainfall events. Intervention comparison for this catchment should therefore be focused on short rainfall durations. This correlates with UK government guidance indicating that short duration storms should be assessed when examining urban catchments without knowledge of critical storm duration (Environment Agency 2013).

Identification of catchment flood dynamics using this approach can steer prioritisation of computationally expensive hydraulic modelling through highlighting design rainfall which is likely to lead to the peak flooding in the catchment. The advantage of this prior investigation is to streamline the modelling process whilst minimising assumptions regarding catchment flood response by evidencing selection of rainfall.

Visualising peak flooding during the critical event

Figure 5 shows a comparative flood depth assessment for each intervention versus the do nothing scenario during the one-hour 200-year return period rainfall event. Absolute flood depth is shown for the do nothing scenario (blue). Intervention effects on flood depth are shown on a separate scale showing improvement in a cell (green) or deeper flooding (red). This shows the largest reduction in flood extents are caused by rainwater capture tanks and upgrading sewer capacities. Reduction in flood depth across the catchment was not uniform, with interventions creating localised

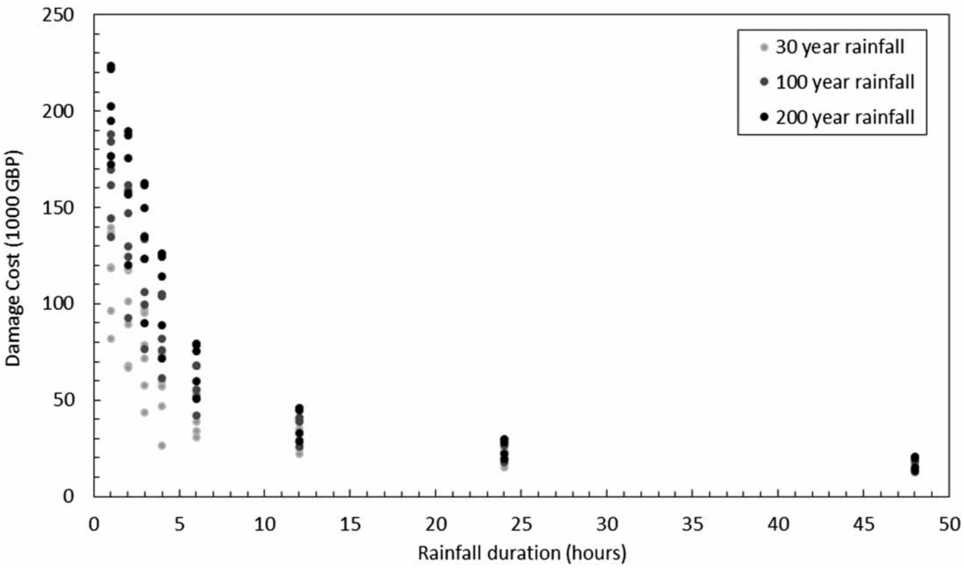

Figure 4 | Catchment critical rainfall duration identified using a damage assessment for all interventions during 30-, 100- and 200-year rainfall events (144 simulations).

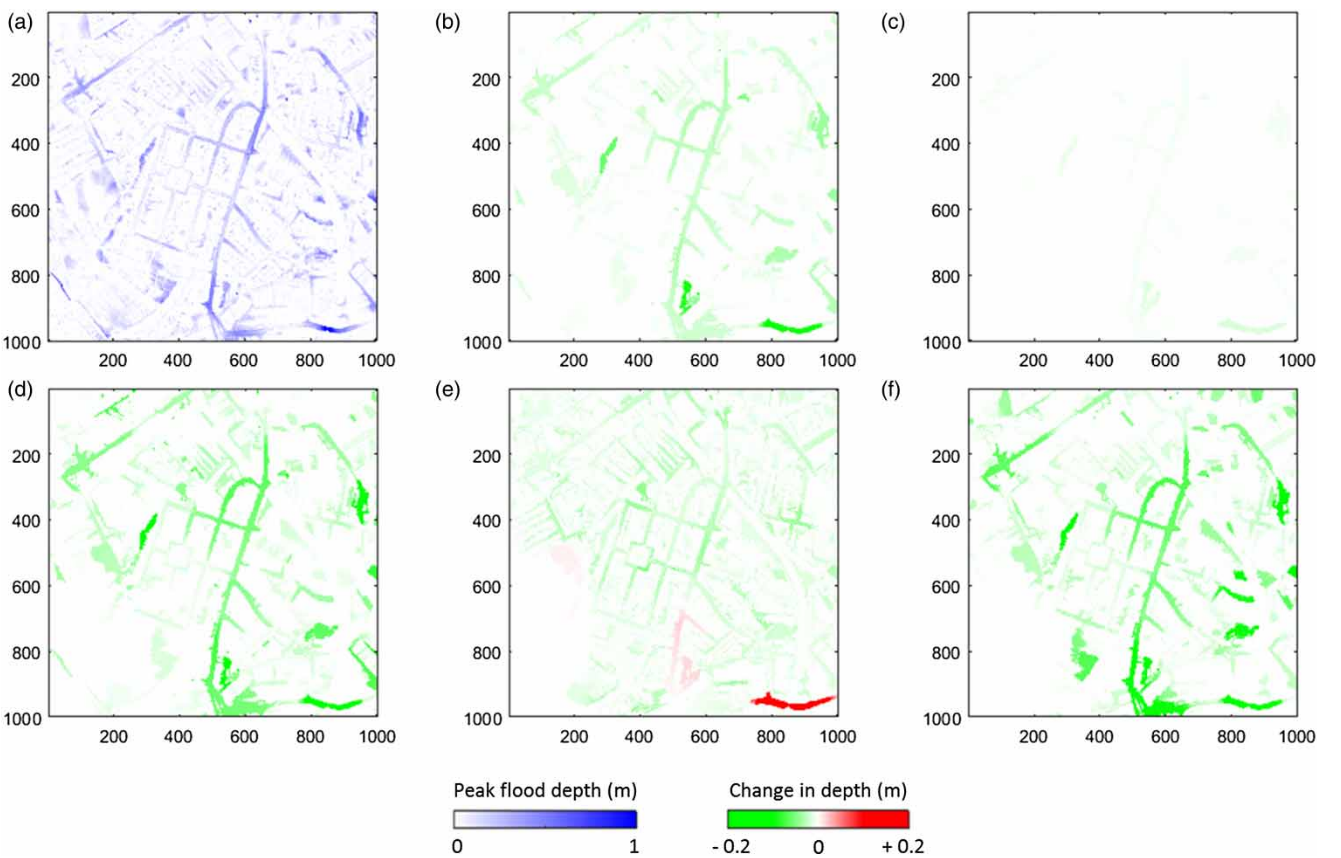

Figure 5 | Peak flood depths during a one-hour 200-year return period rainfall event: (a) do nothing, (b) green roof, (c) water butt, (d) rainwater re-use, (e) permeable paving and (f) upgrade drainage. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2018.122.

regions of improvement, often associated with the road network.

The largest flood reduction is visible in upgrading the drainage system and installing rainwater re-use across the catchment. These strategies show around 20 cm of flood reduction across a large extent of the catchment, with the majority of the benefit being associated with the transport network. It should be noted that areas where no reduction is apparent can also mean that there is no flooding to reduce.

Examining peak depth visualises a snapshot of total flood effect, which is particularly useful for communicating risks and an overview of strategy effects to stakeholders. However, analysis of peak depths does not represent the flood dynamics at any one particular time and so may be unsuitable for uses such as emergency planning where understanding flood movement is required.

Examining the performance of intervention strategies

Interventions which appear to reduce flood extent most significantly do not necessarily correlate with those which show the largest damage cost reduction, due to flood reduction not coinciding with building location. This distinction is important, as flood management should prioritise impact reduction over hazard reduction, particularly when considering placement of surface flooding interventions where location will affect flood extent. This highlights the advantages of a damage cost assessment (Figure 3) over proxy measures of impact (Figure 5), such as captured volume or intervention effects on a sub-catchment scale, and emphasises the need to run flood simulations when comparing intervention strategies.

Figure 6 expands the intervention assessment to assess impact by breaking down damage costs for each intervention strategy across each event. Shorter-duration higher-intensity events lead to the highest flood costs. In all cases the do nothing scenario demonstrates the highest total flood costs, demonstrating all intervention strategies have a benefit.

The strategy with the lowest damage costs for the one-hour event is rainwater re-use. This is despite appearing not to have as large a reduction versus drainage improvements when assessing peak flood depth and extent (Figure 5). The larger reduction in impact with a lower reduction of hazard extent is associated with the location of rainwater re-use preventing surface water accumulation in and around properties, versus the drainage upgrades having a larger effect outside of these. Including a flood depth damage function across the transport network may show a larger impact reduction associated with drainage systems. This example highlights the importance of understanding hazard versus impact reduction.

Drainage upgrades demonstrate the lowest damage costs during the higher-intensity longer-duration events. This is due to the rainwater re-use capture capacity being exceeded over long-duration rainfall. Conveyance-based systems, such as drainage upgrades, can continue to function throughout the event and so lead to lower flood damages. This study has limited analysis to the role of individual intervention strategies; appreciation of the advantages of each approach provides evidence for further performance improvements using hybrid strategies.

Assessing resilient performance of interventions

Resilient performance is assessed through analysis of impact in extreme events (Butler *et al.* 2016). Frameworks which

30 year rainfall

	Green roof	Water butt	Rainwater re-use	Permeable paving	Drainage upgrade	Do nothing
1 hour	119	137	82	119	97	139
2 hour	101	117	68	90	67	118
3 hour	78	95	44	71	57	97
4 hour	60	74	26	57	47	74
6 hour	54	54	31	39	34	54
12 hour	34	35	33	25	22	35
24 hour	23	24	22	17	15	24
48 hour	17	17	17	13	13	17

100 year rainfall

	Green roof	Water butt	Rainwater re-use	Permeable paving	Drainage upgrade	Do nothing
1 hour	170	184	135	162	144	188
2 hour	147	159	125	130	93	162
3 hour	124	134	106	100	77	135
4 hour	104	105	82	76	62	105
6 hour	68	68	56	51	42	68
12 hour	39	41	39	29	26	41
24 hour	27	27	27	19	18	27
48 hour	19	19	18	14	13	19

200 year rainfall

	Green roof	Water butt	Rainwater re-use	Permeable paving	Drainage upgrade	Do nothing
1 hour	203	222	172	195	177	224
2 hour	176	188	157	157	120	190
3 hour	149	161	135	123	90	163
4 hour	125	126	114	89	71	126
6 hour	79	79	75	60	51	79
12 hour	45	46	45	33	29	46
24 hour	29	29	28	22	19	29
48 hour	20	20	20	15	13	21

Damage cost (1000 GBP): 0, 50, 100, 150, 200, 250

Figure 6 | Intervention response to rainfall duration increase.

enable assessment of many simulations have the additional advantage of being able to simulate intervention response to conditions beyond design standards. Figure 7 shows the change in damage costs from each intervention strategy versus increasing rainfall intensity during the two-hour storm in design standard and extreme events.

Interesting implications for resilience can be identified by the shape of the curves for each intervention in Figure 7. Interventions generating a shallower gradient demonstrate an ability to minimise damage beyond the standard design conditions, resulting in a more resilient performance relative to other scenarios. Some interventions exhibit a shallow curve for low return periods, which steepens as higher return periods are reached, indicating failure in levels of service.

During the 30-year return period, the intervention strategies resulting in minimum damage costs are rainwater re-use and drainage upgrades. Permeable paving also performs well, but causes approximately 20,000 GBP more damage. The same performance ranking applies to the 100-year event, but the difference between rainwater re-use and permeable paving has narrowed, whilst drainage upgrades shows a more stable increase in costs. During the 200-year event rainwater re-use results in higher damage costs than permeable paving, with drainage upgrade damage now more than 35,000 GBP less.

Variation in performance highlights the importance of assessing impact across multiple return periods and durations when selecting surface water management interventions, providing evidence that the current paradigm of restricted consideration of events is not sufficient to ensure the best outcome in response to uncertainties in future climate and urban growth. This information can be presented as part of decision support to complement a standard

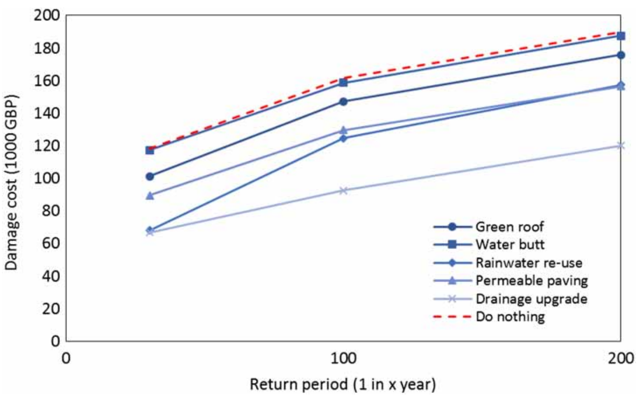

Figure 7 | Damage cost versus increasing rainfall intensity during the two-hour rainfall event.

assessment and has the potential to promote innovative interventions which meet design standards during high-probability events, whilst providing additional resilience for low-probability occurrences.

General guidance and limitations

The framework presented in Webber *et al.* (2018) has been developed to screen intervention strategies in an urban catchment. Quantitative analysis of flood depths and damage costs provides a simple metric to evidence decision support, offering an advantage versus fast but qualitative screening tools such as stakeholder ranking (Ellis *et al.* 2004; Martin *et al.* 2007; Makropoulos *et al.* 2008; Young *et al.* 2010) and GIS analysis (Weng 2001; Makropoulos *et al.* 2007; Ellis & Viavattene 2013). It should be noted that the simplified representation of physical parameters such as infiltration and the lack of a 1D drainage network mean that this approach is not suited to detailed hydraulic design. Further capabilities could be added to the assessment framework through examination of intervention cost-effectiveness and finer resolution placement of intervention strategies.

The key recommendation from this study is to screen many strategies prior to detailed design due the observed variation in performance across rainfall intensity and duration. Suggested improvements to the approach include examining combinations of intervention strategies, which may provide a more robust response to a larger range of events. There is also merit in building on the resilience assessment principles presented here by expanding the number of return periods assessed.

CONCLUSIONS

The framework was able to simulate large numbers of intervention and rainfall scenarios, taking advantage of CA simulation speeds with a simple input process. Screening many interventions outputs evidence capable of directing decision makers towards further examination using detailed hydro-dynamic approaches. Utility of the framework was demonstrated through analysis of rainfall duration, intervention type and discussion of initial steps towards a new resilience assessment approach suitable for surface water interventions. A fast and resource-efficient method for quantifying flooding will promote inclusion of many strategies, providing a platform for new and innovative interventions.

Future research will focus on including new interventions, formalising the resilience assessment and investigating cost-beneficial strategies. Representations of interventions will also be benchmarked against case studies to improve the accuracy of this approach.

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