Received: 6 May 2020 | Revised: 2 March 2021 | Accepted: 17 March 2021

DOI: 10.1111/jfr3.12723

ORIGINAL ARTICLE

CIWEM Chartered Institution of Water and Environmental Management | Journal of Flood Risk Management | WILEY

Targeting property flood resilience in flood risk management

James L. Webber[1] | **Albert S. Chen**[1] | **John Stevens**[2] | **Rob Henderson**[3] | **Slobodan Djordjević**[1] | **Barry Evans**[1,4]

[1]Centre for Water Systems, University of Exeter, Exeter, UK

[2]Bristol City Council, Bristol, UK

[3]Wessex Water, Bristol, UK

[4]Massey University, Palmerston North, New Zealand

Correspondence

James L. Webber, Centre for Water Systems, University of Exeter, Exeter, UK.
Email: j.webber2@exeter.ac.uk

Funding information

European Commission, Grant/Award Numbers: 244047, 700174; Natural Environment Research Council, Grant/Award Number: NE/P011217/1

Abstract

In this article, we evaluate property flood resilience (PFR) to manage pluvial and combined tidal/ fluvial flood risks. We achieve this by evaluating flood risk and intervention targeting strategies across a case study in Bristol (UK) using data types generally available for preliminary option assessment. We investigate opportunities for mitigating flood damages within catchments using PFR and evaluate two targeting strategies: Installing PFR across strategic areas of a catchment and targeting interventions at specific high-risk properties. We find that individually targeting PFR is more effective than focusing resources on specific high-risk areas. Targeting pluvial flood measures at individual properties across our case study provides an average annual benefit per property of approximately £750 more than applying zonal targeting, supporting use of high-resolution modelling in surface water management, and highlighting the applicability of PFR to manage damages at specific high-risk properties which may not fall under the protection of community level defences. A similar approach provides the best outcomes for fluvial targeting; however, the hazard is more concentrated and so a zonal targeting approach may be more acceptable. Overall, we find resistance based PFR an effective intervention to mitigate damages, however complementary strategies are required when managing extreme flooding.

KEYWORDS

flood mitigation, fluvial, pluvial flooding, property flood resilience, urban flooding

1 | INTRODUCTION

In this article, we develop a methodology to evaluate the flood reduction benefits of property flood resilience (PFR), applicable generally using resources and data typically available in flood risk management. The key messages from our work include illustrating how this methodology can be applied in decision support to evaluate different PFR targeting strategies, and the advantages of integrating property-scale resolution across catchment-scale analysis when doing so. Our findings are supported by analysis of a case study in Bristol, UK.

Effective flood risk management is a vast and global challenge (Hallegatte, Green, Nicholls, & Corfee-Morlot, 2013; IPCC, 2014; Shah, Rahman, & Chowdhury, 2018). Policy makers across the world are aware of the current significant risks to lives, infrastructure, and communities that the threats from climate change, natural hazards, and aging drainage systems are likely to exacerbate (Carter, White, & Richards, 2009; Committee on Climate Change, 2017; Wong & Eadie, 2000). However, despite established understanding of future threats, new evidence indicates that the scope and scale of these challenges has been systematically under-estimated, and in fact, these threats are likely to represent a greater challenge than previously anticipated (Guerreiro, Dawson, Kilsby, Lewis, & Ford, 2018; Wing et al., 2018). Compounding this ever-growing threat are the economic pressures faced by decision makers and a growing trend towards populations migrating into cities (Djordjević, Butler, Gourbesville, Mark, & Pasche, 2011; Wong & Brown, 2009). It is therefore crucial that research develops urban management strategies to protect properties, infrastructure, and people.

Decision makers have responded to these threats through developing a range of flood management frameworks, often including highly accurate hydrodynamic models (Chen, Djordjević, Leandro, & Savić, 2010; Elliott & Trowsdale, 2007; Hunter et al., 2008; Jayasooriya & Ng, 2014; Néelz & Pender, 2013; Schubert, Burns, Fletcher, & Sanders, 2017; Viavattene & Ellis, 2013). These models feed into established risk management approaches, such as UK based Surface Water Management Plans (SWMP) and Strategic Flood Risk Assessments (SFRA) (DCLG, 2010; DEFRA, 2010; HM Government, 2010). However, despite this understanding and over a decade of legislation, there are still significant barriers to the implementation of flood risk management strategies, particularly those reliant on novel and distributed interventions (Commitee on Climate Change, 2015; HM Government, 2010; Pitt, 2008; Thorne, Lawson, Ozawa, Hamlin, & Smith, 2018).

In response, research has developed a diverse range of flood management interventions, including conventional piped drainage networks, sustainable drainage systems (SuDS), green infrastructure, PFR, nature based solutions and catchment management, to name a few (Butler, Digman, Makropoulos, & Davies, 2018; Fletcher et al., 2015; Schanze, 2017; Woods Ballard et al., 2015). A potential area of opportunity which has not yet been fully exploited is flood management using decentralised interventions and PFR (Bowker, 2007; Environment Agency, 2015b; White, Connelly, Garvin, Lawson, & O'Hare, 2018). PFR aims to reduce water ingress, stress and damage to properties using structural elements such as flood gates and waterproofing building fabrics (Bowker, 2007; Golz, Schinke, & Naumann, 2015). Research has found these measures to be economically worthwhile when properties predicted to flood at a 25-year return period are treated (Thurston et al., 2008).

Although understanding of PFR at a site-scale is well understood, with significant UK policy and technical guidance (BSI, 2015; DEFRA, 2012, 2014; Environment Agency, 2007; Lamond, Rose, Bhattacharya-Mis, & Joseph, 2018), it remains under-exploited, with several key barriers to implementation (White et al., 2018). One such barrier highlighted within recent PFR evidence reviews (Lamond et al., 2018) is the limited application of high-resolution modelling, with many analyses relying on general evaluation of national datasets and long term analysis of stochastic risk profiles representing a tranche of properties, as opposed to applying advanced modelling to consider flood risk at a property-scale. Similarly, tools for spatial analysis of strategy benefits and consideration of how these accumulate under a range of targeting strategies, and in response to different flood types and depths, is still lacking (DEFRA, 2012), leading to ad-hoc application as opposed to coordinated evaluation across local contexts. This issue is synonymous with other distributed flood management measures, which studies highlight would benefit from developing consistently applicable institutional decision support methodologies, developing stakeholder tools and evidence to understand application across the catchment-scale and integrating application into local and strategic contexts (O'Donnell, Lamond, & Thorne, 2017; White et al., 2018).

In this study, we respond to these research gaps through evaluating how PFR can be targeted at a catchment-scale to manage flood risks. We approach this through developing a methodology, grounded in replicable data, which combines established conventions and products in a novel way to integrate a high-resolution property-scale perspective within catchment-scale decision support.

Our study is complemented through a case study in Bristol, UK, where we have co-developed analysis with engaged stakeholders including Bristol City Council and Wessex Water, providing additional opportunities to develop trust and enhance consideration of novel interventions through supporting the science-practice interface (Jasanoff & Wynne, 1998). Furthermore, our method takes advantage of data types and products, which are well established, trusted, and commonplace in flood management, enabling general application of our methods for international audiences.

2 | METHODS

We investigate our research questions through applying a flood management framework to a case study in Bristol, South West UK. We selected this case study due to well-formed stakeholder partnerships providing access to data, engaged feedback and the potential for implementation, which are all detailed further later in this article. Although findings from this report are specific to Bristol, the method and specific general lessons are applicable to evaluate and understand intervention analysis and effectiveness in similar large urban areas. This is particularly relevant in England, where the sorts of large data sources (Local Flood Risk Management Strategy, SWMP, and Environment Agency data-sets) applied for analysis are mandated by law and thus generally available (DCLG, 2010; DEFRA, 2018; HM Government, 2010). Similar data are also available across the remainder of the UK and internationally.

2.1 | Bristol case study

We evaluated the effectiveness of PFR targeting strategies through analysis of a case study in Bristol City Centre. The case study was selected due to the high availability of data, particularly high-resolution fluvial and pluvial flood modelling, made possible through key stakeholder partnerships formed with the city council and water utility company as a part of the EU funded RESCCUE (resilience to cope with climate change in urban areas) project (Velasco et al., 2018). We note that the article does not reflect an option assessment or wider flood risk management strategy for Bristol, the approach is purely an analysis of PFR targeting.

Bristol is the largest city in South West England, with a population of over 450,000 (Bristol City Council, 2019). The city is located on the coastline and is home to many services of national and regional significance, including access to a large commercial port. Flood hazards in the city centre originate from a range of sources including pluvial runoff and fluvial flooding exacerbated by the tidal locking of outfalls and watercourses. Bristol is highlighted in the top 10 pluvial flood risk areas in England, with 22,300 homes at risk (Bristol City Council, 2018). Fluvial flood hazard is also significant from the River Avon and its associated watercourses, notably including the 1968 floods in which seven deaths were recorded. Fluvial flood risk is exacerbated by situation adjacent to the Severn Estuary, the second highest tidal range in the world. This tidal influence extends into the city centre and previous flood events have been worsened by tide locking during intense rainfall. This includes flooding in 1981 when 12 properties flooded (Bristol City Council, 2018). The City Council predict that approximately 1,000 properties are at risk from tidal surge flooding in the present day.

2.2 | Representing land use

We obtained land-use data for Bristol through the UK Environment Agency National Receptor Dataset (NRD; Environment Agency, 2014). The NRD contains point data describing building types. We overlaid this point data on building polygons from the UK Ordnance Survey Mastermap to attribute building types to the spatial extent of specific structures (Ordnance Survey, 2020). Figure 1 presents the distribution of land-use classification areas within the study area. The predominant land use is residential properties.

2.3 | Flood hazard modelling

We applied existing high-resolution hydrodynamic modelling to define flood depth, extent, and probabilities across the study region. Modelling consisted of a range of flood hazards, including pluvial and fluvial/tidal flood risk. We evaluated each flood hazard through a range of return periods and two management scenarios: a present-day baseline and a 'business as usual' future scenario, taking account of likely climate change.

The baseline scenario represents the study area 'as is' assuming the current land-use and climatic conditions for rainfall generation. We used this scenario as a comparison with which to identify changes associated with future management options. Management options include positive (in the case of interventions) and negative (in the case of climate change increasing rainfall) changes to the study area and baseline hydrology.

The business-as-usual scenario (BAU) represents future flood risk in 2115 assuming climate change mitigation practices remain the same as currently employed. This includes an uplift for rainfall intensity and peak river flows, as specified in UKCP09 and a sea level rise/tidal range uplift in accordance with the upper-end increases predicted within the Severn River Basin District (DEFRA, 2009; UK Government, 2020).

Pluvial flood modelling is provided by the Bristol SWMP (Bristol City Council, 2012). The SWMP is an integrated urban drainage model including representation of the 1D sewer network and 2D ground surface. The model was originally completed using the Microdrainage WinDes FloodFlow package and has since been updated in the Infoworks ICM model software.

The SWMP includes simulation of large-scale rainfall events to identify areas at significant risk of pluvial flooding. This comprises multiple storm durations and climate change allowances, fully described in the associated SWMP report (Bristol City Council, 2012). For the purposes of this analysis, we have evaluated 10, 30,

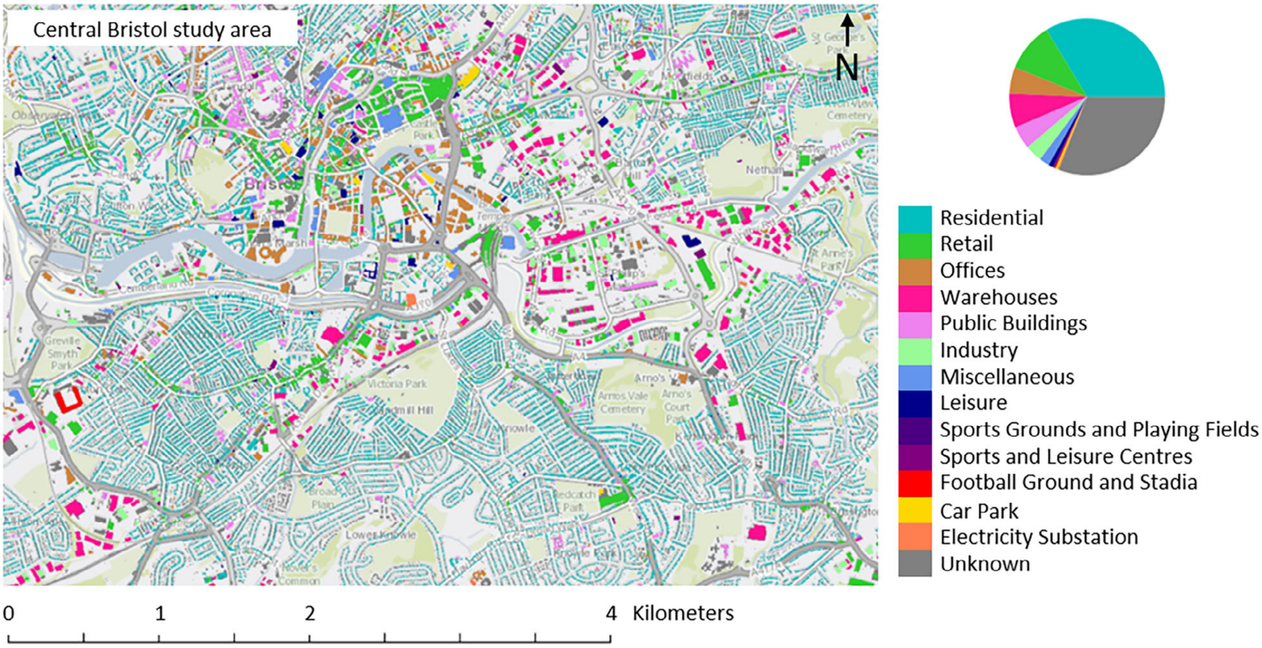

FIGURE 1 Land use classification across the Bristol City Centre case study

and 100-year return periods to describe the baseline and 10, 20, and 100-year return periods to describe the BAU scenario. Ideally, we would have preferred to match these return periods, however, this was not possible given the modelling resources available. As such, we applied a range of rainfall probabilities, from relatively frequent events, through to extreme events, now and in the future.

Fluvial flood modelling and tidal influences was included using the Bristol Central Area Flood Risk Assessment (CAFRA; Bristol City Council, 2015; Hyder Consulting, 2013). CAFRA included a full 1D–2D coupled ISIS-TUFLOW hydraulic model, which included a full joint probability assessment of the interaction with tidal and fluvial flooding and output flood extent, depth, and velocities. The model was developed by Hyder Consulting and subject to a full review from Bristol City Council and a third-party reviewer, JBA Consulting. Full details are available in the Bristol CAFRA Summary Report (Bristol City Council, 2015; Hyder Consulting, 2013). As with pluvial flooding, we selected a range of return periods to evaluate across the study in relatively frequent and extreme scenarios. This included 20, 100, and 200-year events in the baseline and 20, 200, and 1,000-year events in the BAU scenario.

Groundwater flooding was not included in this study as it is considered to be of much lower risk than other sources within the study area (Bristol City Council, 2018). However, it should be noted that localised groundwater flooding in basements may be an issue in low lying areas of the city.

TABLE 1 Scenarios evaluated in the Bristol case study

	Fluvial flooding CAFRA	Pluvial flooding SWMP
Baseline • Current land use • Current climate	20, 100, 200	10, 30, 100
Business as usual plus climate change • Flood risk management and land use remains the same • Climate change increases rainfall intensity and volume • Sea level rise leads to greater tides	20, 200, 1,000	10, 20, 100

Table 1 presents a summary of flood scenarios included in this study.

2.4 | Flood damage assessment

We evaluate flood damage attributed to each scenario using a damage assessment tool to calculate direct and tangible flood damages to the structure of each building (Chen, Hammond, & Djordjevic, 2016; Hammond, Chen, Djordjević, Butler, & Mark, 2015; University of Exeter, 2014). The tool functions through spatially analysing the contact of floodwaters with properties and deriving damage estimates per square meter. A damage value for each building polygon is calculated using peak flood depth from hydrodynamic modelling and a depth-damage function. The depth-damage functions are taken from the industry standard UK Multi-Coloured Manual (MCM; Penning-Rowsell, Viavattene, & Parode, 2010) and are specific to each building classification outlined in the NRD (Environment Agency, 2014). Application of standardised damage curves from the MCM ensures that our methodology remains comparable (at a high-level) with existing modelling studies, supporting our intention to enhance a preliminary relative comparison of novel distributed flood management measures with other, more commonplace, approaches.

We calculated total damage per return period by summing damages of all polygons for the peak depth at each location across the simulation. Damage is only related to depth, without consideration of velocity or other damaging factors such as contamination (Merz, Kreibich, Schwarze, & Thieken, 2010). Intangible and indirect damages have not been included within this assessment (Hammond et al., 2015).

We synthesised damages from each simulation into an estimated annual damage (EAD) for each scenario by sampling damages from all return periods and integrating into a single annualised average (Merz, Kreibich, Thieken, & Schmidtke, 2004). Bookmarking this sample across a range of different probability events, including extreme and frequent return periods, generates a curve representing damage across a spectrum of potential outcomes and develops one comparable metric representing each scenario (University of Exeter, 2014).

2.5 | Representing PFR

One objective of our study was to represent intervention effectiveness using the types of modelling resources likely to be commonly available to a wide range of potential case study cities, thus providing an opportunity towards considering PFR within general flood risk assessments. As such, we included analysis of interventions through adjustments to the flood-damage curve described in the previous section.

PFR aims to reduce water ingress to a property by flood-proofing areas through installation of measures such as flood barriers, water-proof membranes and air brick covers, among others (DEFRA, 2012; Lamond et al., 2018; White et al., 2018). Literature indicates that these types of measures are effective up to approximately 600 mm of standing water (Bowker, 2007; Bowker, Escarameia, & Tagg, 2007; Ingargiola, Jones, & Quinn, 2012; Lamond et al., 2018; White et al., 2018). Some studies suggest flood proofing may be effective up to 900 mm (Environment Agency, 2015a). However, others specify that the effectiveness of flood proofing products may be limited by the structural integrity of the building they are protecting when water depth exceeds 600 mm, and as such protection cannot be guaranteed over this height (Bowker et al., 2007; US Army Corps of Engineers, 1988). We have applied a conservative approach to avoid over estimation of intervention effectiveness and have therefore adopted an intervention effectiveness value of up to 600 mm.

We have represented this intervention in our analysis through adjusting depth-damage curves for protected buildings to show no damage up to the 600 mm effectiveness threshold (assuming no structural modifications/reinforcement to the property). Figure 2 shows the depth-damage curves for two residential properties: one with and one without PFR adaption. We assume no damage up to the threshold, and then normal damages (due to overtopping) once flooding exceeds the threshold.

We have focused on residential flood damages and not evaluated the effect of PFR on other property types. This is due to the wide variation of PFR characteristics and associated damages on other building types and the government priority for residential flood protection.

2.6 | PFR targeting strategies

Evaluating full cost–benefit of PFR for targeting placement strategies typically requires detailed analysis on a case-by-case basis. However, the Environment Agency technical report (Thurston et al., 2008) indicates that investment in permanent resistance based PFR is economically viable when applied to properties vulnerable to flooding within the 25-year return period. This report estimates a cost benefit of 1.6 per £1 spent. Installation and maintenance costs from this report are based on 'Kitemark' approved products provided by flood product manufacturers and previous research (ABI, 2003, Norwich Union, 2005). Evidence reviews, such as Lamond et al. (2018) indicate that literature highlights "exclusionary-based" PFR (measures designed to resist ingress) can be cost effective if applied to properties with a return period of 40–50 years. However, for the purposes of this strategic research we have based our placement of PFR on meeting a threshold of a conservative 20-year flood event.

We applied two intervention placement methods within our study: Strategic intervention areas and individually targeted interventions.

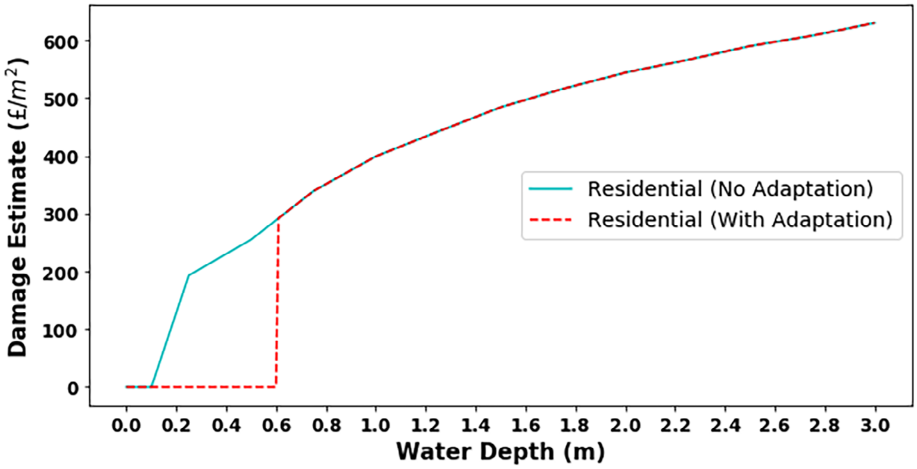

FIGURE 2 Depth-damage curves for residential properties with and without property flood resilience

Strategic intervention areas represent a typical high-level approach for targeting interventions where all properties within the area are treated with the intervention. We based targeting areas on local authority 'super output areas'. Super output areas are a geographic hierarchy delimited by the UK Government. Each super output area is designed to contain a comparable population size, and this unit is therefore effective and comparable for investigating small area statistics in England and Wales. In terms of flood analysis, super output areas can also be considered indicative of the scope of a community level flood defence scheme. Flood damage for all super output areas was aggregated during the 20-year BAU flood event and all properties within the top three flood risk areas were selected for intervention. We performed this analysis separately for fluvial and pluvial flood hazards. The three fluvial flood risk super output areas with the highest aggregated damage contained 235 residential properties, and the top three pluvial areas contained 339.

Individually targeted interventions were developed as comparative analysis to the zonal approach. For this strategy we selected the same number of properties identified for the relevant flood mode in the zonal analysis and then applied interventions to the individual properties with the highest flood damages, regardless of their location in the study area. This included 235 and 339 residential properties in the fluvial and pluvial analysis, respectively.

3 | RESULTS

3.1 | Fluvial flood damage

Figure 3 presents fluvial flood damage under a tidal influence during the 20-year BAU event aggregated to the local super output area scale. Fluvial flooding causes the highest flood damages in the downstream area (left) where the tidal influence is strongest. This is of particular concern in the central 'Harbourside' area of the city, a hub of commerce and entertainment, where between £1 and £3 million in damage is estimated per super output area. Damage is concentrated around the watercourses, with far lower damage values (<£500,000) upstream of the city centre. The three super output areas with the largest expected flood damages are all located in close proximity to each other and adjacent to the watercourses.

Figure 4 develops analysis of flooding to present the fluvial flood damage aggregated by building types across all flood scenarios. The most significant result is the almost 15-fold increase in flood damages between the baseline and BAU events. For example, flood damages in the 20-year flood event baseline are around £12 million, whereas under BAU these rise to over £150 million.

The majority of baseline damages are attributed to warehouses, industry, and unknown receptors. Future risk also impacts retail and office premises. Damage to residential properties is low during current conditions, although increases significantly in the BAU scenario.

Figures 5 and 6 combine return periods to develop a comparable EAD metric. These figures indicate that present loss is estimated at £0.8 million per year, but that this is anticipated to rise to £11.8 million by 2115.

Figures 5 and 6 also present the effectiveness of PFR in mitigating losses. Zonal targeting is estimated to benefit the catchment by approximately £0 (baseline) to £170,000 (BAU) per year, whereas individually targeted interventions are expected to realise a damage reduction of £100,000 (baseline) to £220,000 (BAU). This represents a relatively small proportion of flood damages caused by fluvial flooding, particularly in the baseline scenarios; however, this should be understood in the context of the small number of properties located in the baseline flood risk area. The benefit increases during the BAU scenario but is significantly lower than the very high EAD values due to predominance of flood damage to warehouses, industry and office space located in the flood area.

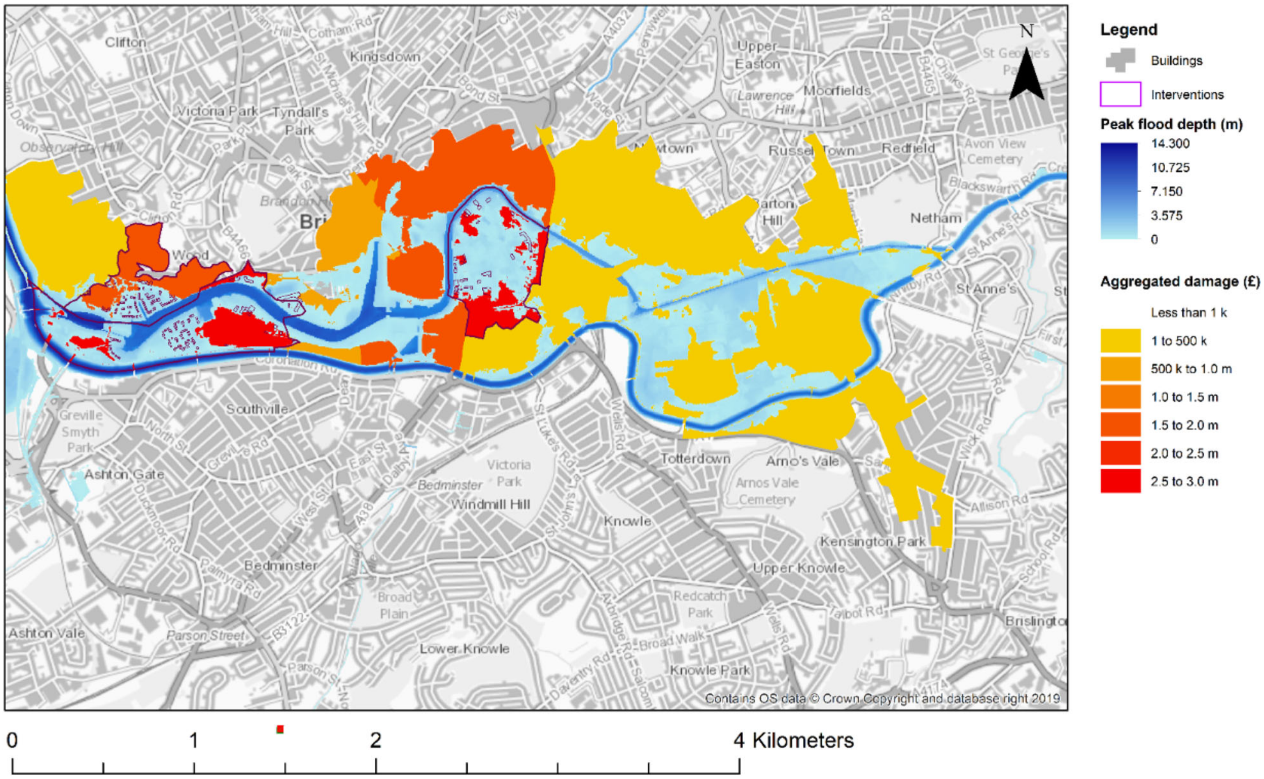

FIGURE 3 Aggregated damage across local authority super output areas in the BAU 20-year fluvial flood scenario (235 properties are located within the three super output areas with highest aggregated damage)

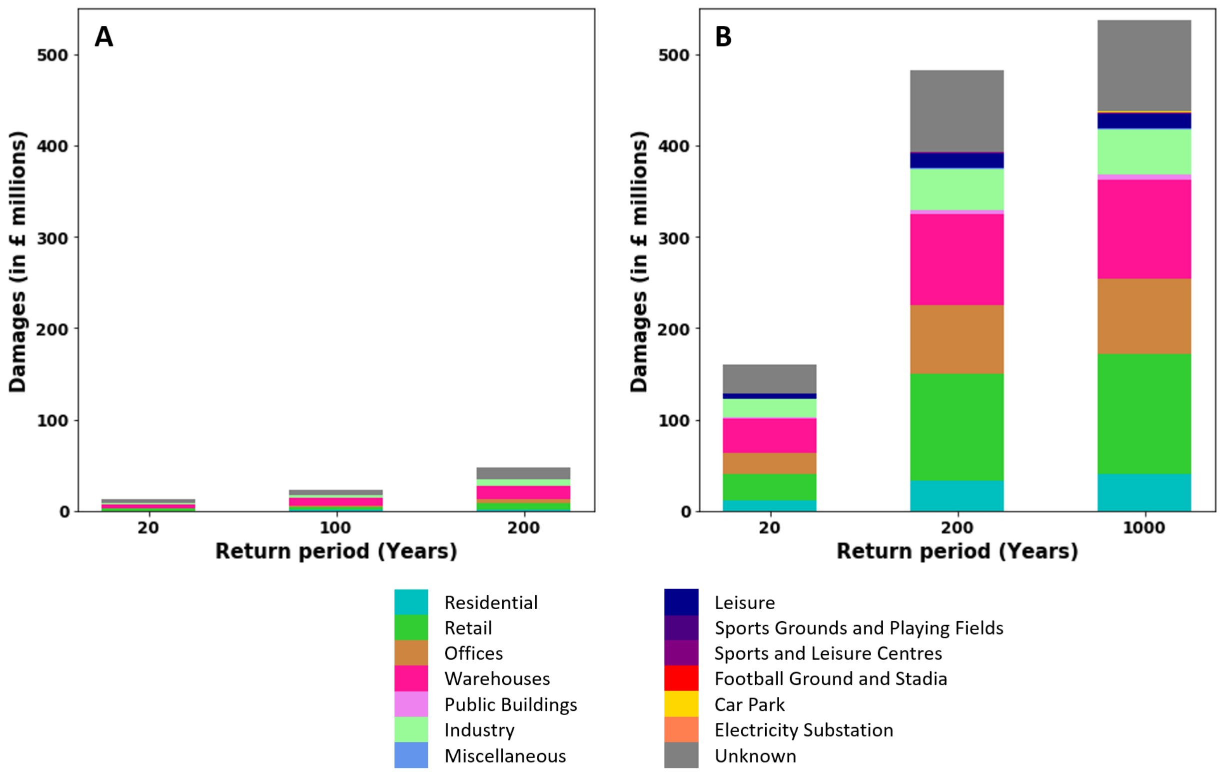

FIGURE 4 Fluvial flood damage by building type across return periods: (a) baseline scenarios and (b) business-as-usual scenarios

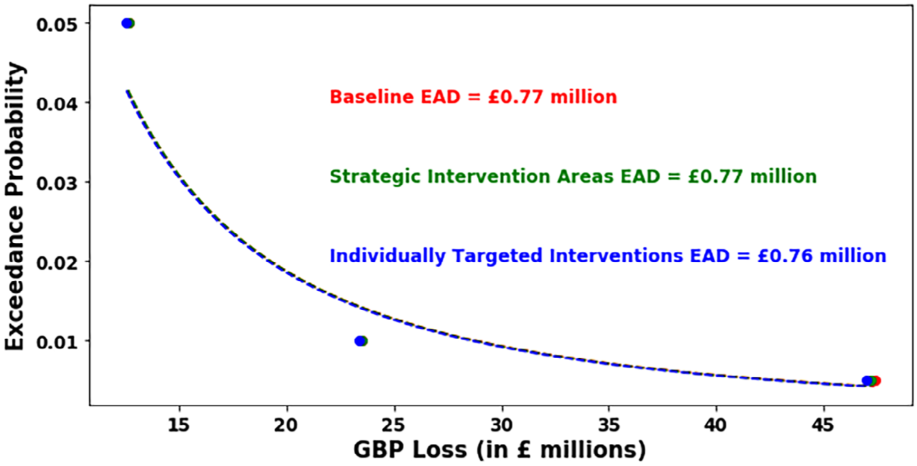

FIGURE 5 Estimated annual damages caused by fluvial flooding in the baseline scenario

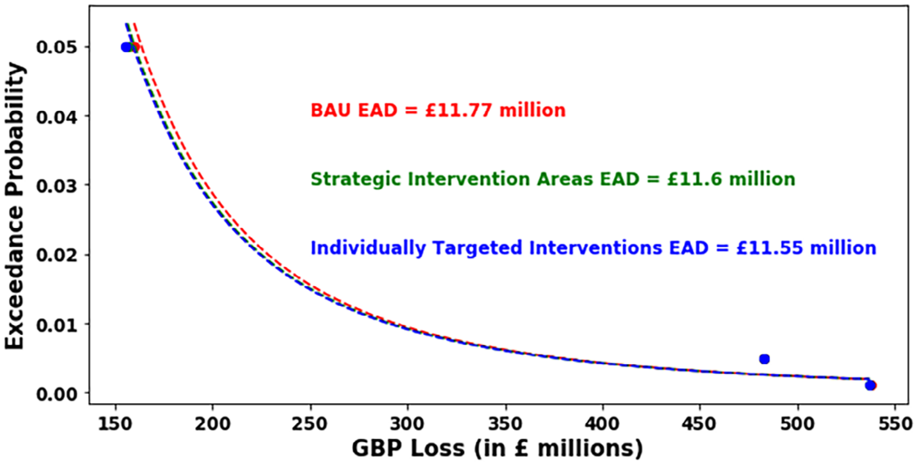

FIGURE 6 Estimated annual damage caused by fluvial flooding in 2115, assuming 'business as usual' practices

3.2 | Pluvial flood damage

Figure 7 presents the spatial pattern of pluvial flood damage aggregated to the local authority super output area during the BAU 20-year flood event. Damage values per super output area are lower than those presented for the equivalent fluvial event (Figure 3), however damages are spread city-wide across the catchment, rather than being focused around watercourses. The three super output areas with the highest flood damages are distributed across the catchment and away from watercourses, making their location difficult to predict without the detailed modelling undertaken as part of the SWMP.

Figure 8 presents pluvial flood damages across all events, aggregated to building types. This indicates that flood damages during the present-day scenario focus overwhelmingly on residential properties. This remains the same for the BAU scenarios. Retail, warehouses, offices, and unknown attributions are also impacted, but not to the same scale as homes.

Figures 9 and 10 combine damages across events to present EAD. This highlights that present day (baseline) pluvial flood damages (£2.5 million) outweigh fluvial flood counterparts (£0.8 million). Pluvial flood damages almost double in the BAU scenario (to £4.8 million), however these do not match the almost 15-fold increase displayed by fluvial flood damages (to £11.8 million).

Figures 9 and 10 indicate that the strategic implementation strategy has a benefit of between £120,000 (baseline) and £160,000 (BAU) per year. Targeting individual properties across the catchment has a much greater benefit of between £390,000 (baseline) and £420,000 (BAU) per year.

4 | DISCUSSION

4.1 | Pluvial flooding is currently the predominant flood hazard in Bristol City Centre

Our results provide evidence that pluvial flooding is the predominant current flood risk in Bristol City Centre.

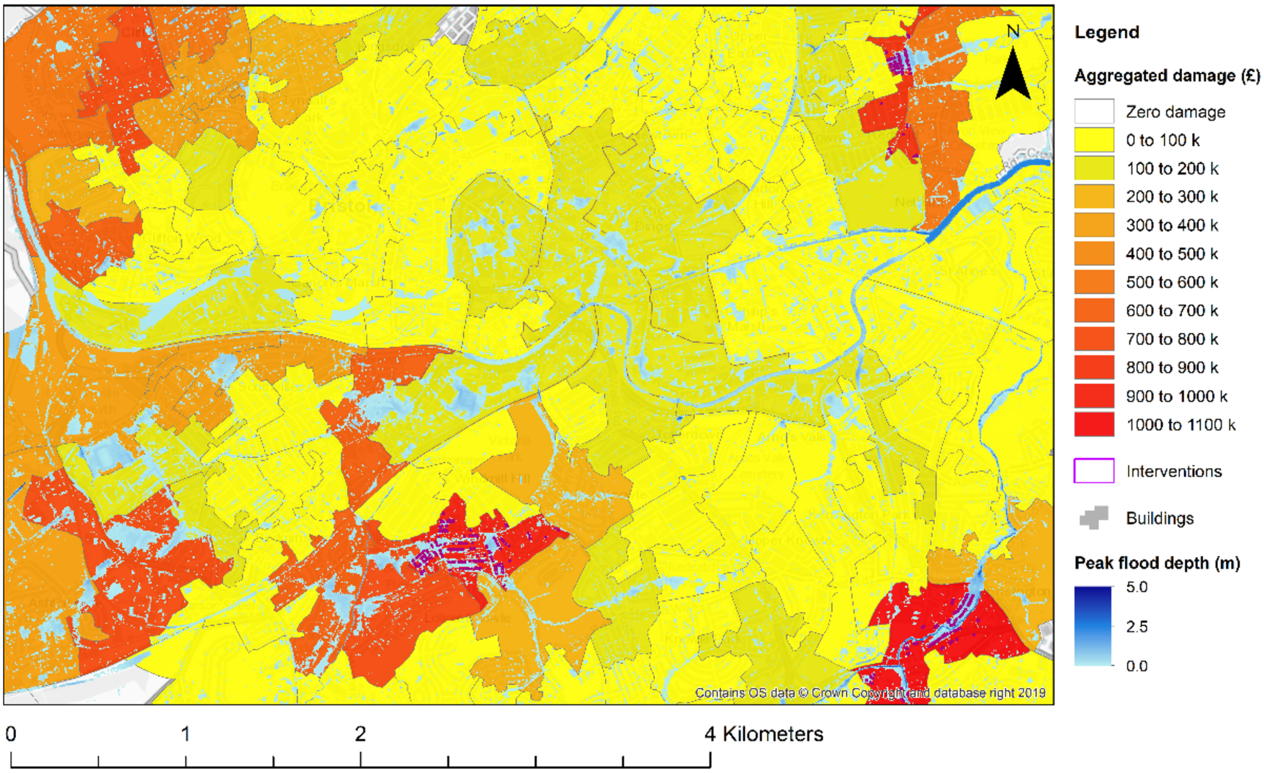

FIGURE 7 Aggregated damage across local authority super output areas in the BAU 20-year pluvial flood scenario

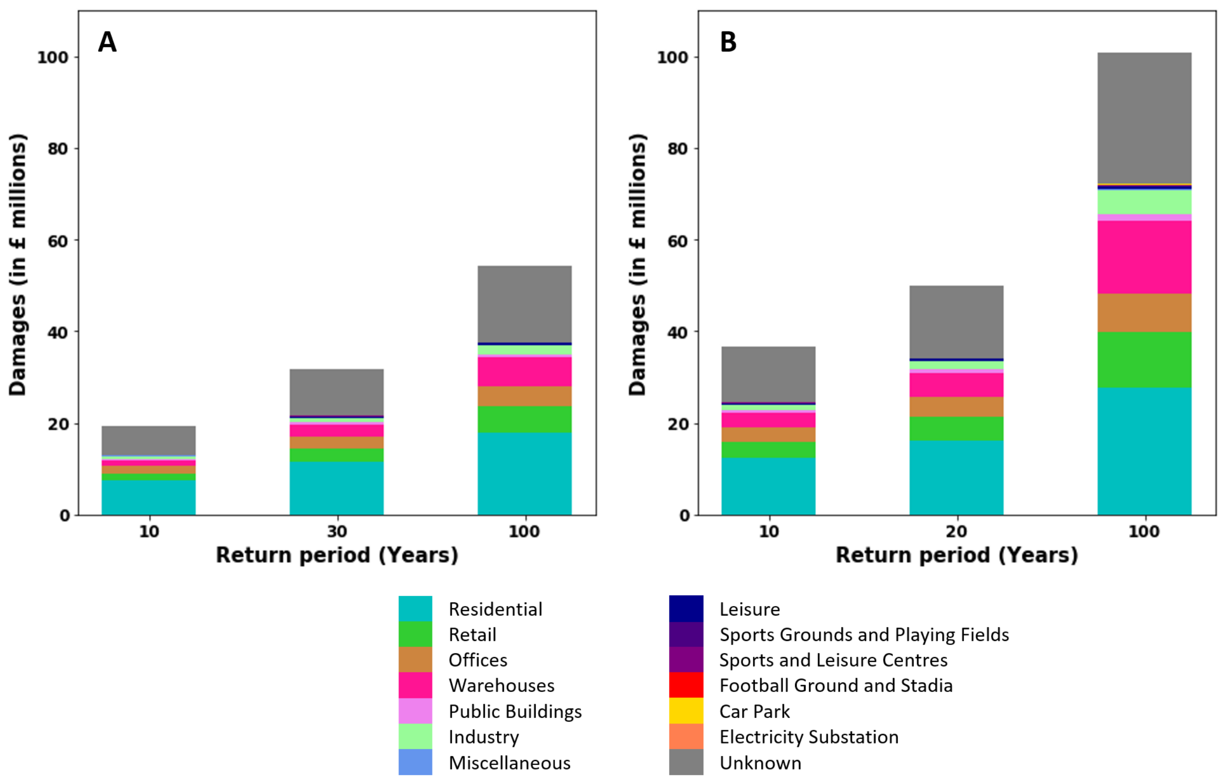

FIGURE 8 Pluvial flood damage by building type across return periods: (a) baseline scenarios and (b) business-as-usual scenarios

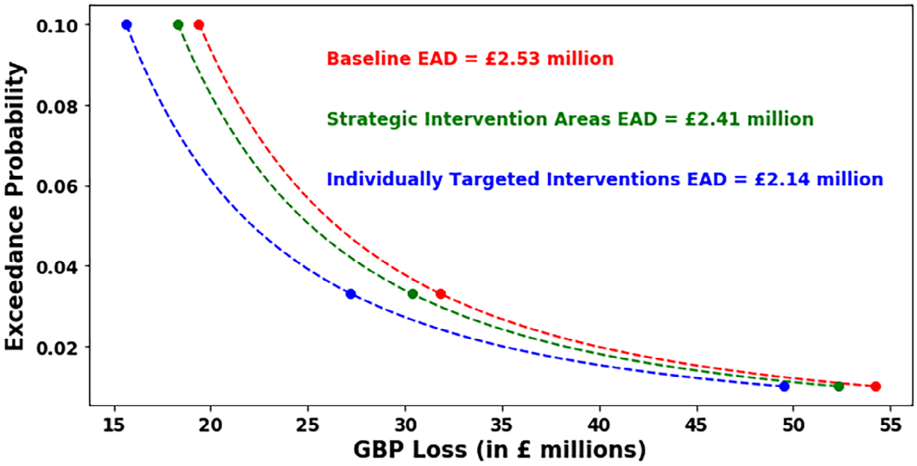

FIGURE 9 Estimated annual damage caused by pluvial flooding in the baseline scenario

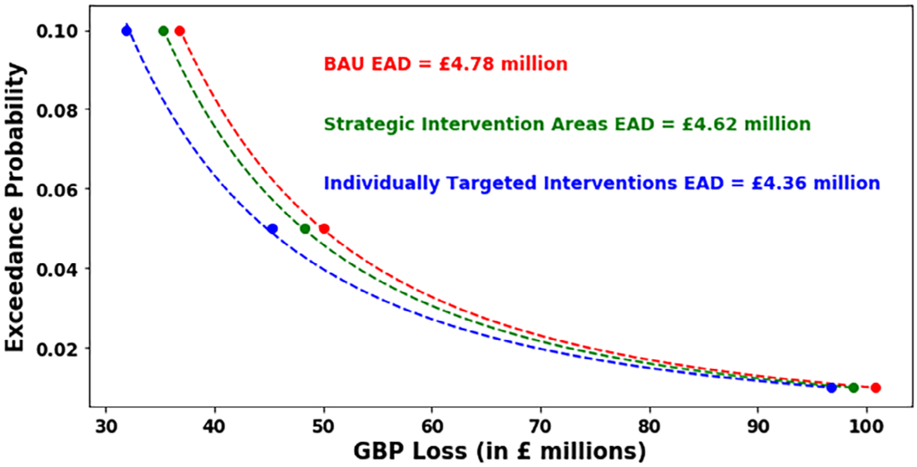

FIGURE 10 Estimated annual damage caused by pluvial flooding in 2115, assuming 'business as usual' practices

This supports earlier studies, such as the Bristol Local Flood Risk Management Strategy, which also prioritise action to manage pluvial flooding in the city (Bristol City Council, 2018). Results estimate the current EAD associated with pluvial flooding is £2.5 million (Figure 9). This is significantly higher than the current EAD of £0.8 million associated with combined tidal/fluvial flooding (Figure 5).

Furthermore, the risk of pluvial flood damage may be under-represented in these figures. It is noted that pluvial flood depths are based on the 1D–2D modelling undertaken for the Bristol SWMP (Bristol City Council, 2012). This modelling assumes a fully functioning drainage system based on current utility records. However, literature indicates that current deterioration of aging drainage systems could result in localised system failures; therefore, in practical terms this risk may be higher due unaccounted sewer condition (Ana & Bauwens, 2010; Fenner, 2000). Furthermore, other studies indicate the strong influence of small-scale features (urban microtopography) on flooding. Micro-topographical features include a range of factors which will influence flow paths at a local-scale, including drainage ditches (Bates et al., 2006), walls (Yu & Lane, 2006), fences (Mignot, Paquier, & Haider, 2006), roads (Fewtrell, Duncan, Sampson, Neal, & Bates, 2011), and buildings (Chen, Evans, Djordjević, & Savić, 2012; Schubert & Sanders, 2012; Syme, Pinnell, & Wicks, 2004). Other features, such as vegetation (Dottori, Di Baldassarre, & Todini, 2013) and pipe blockages, may be temporary, short lived, and almost unpredictable, exacerbating the risk of pluvial flooding in ways not accounted for in current risk management.

These figures are subject to several limitations, such as broad assumptions regarding damage functions and a large number of unknown property attributions. However, use of high-resolution integrated flood models (*SWMP*: Bristol City Council, 2012; *CAFRA*: Hyder Consulting, 2013) alongside industry standard flood depth-damage curves (*MCM*: Penning-Rowsell et al., 2010) and receptor databases (*NRD*: Environment Agency, 2014) means that these limitations are similar to, and thus comparable with, other studies conducted across the UK.

This study has not included groundwater flooding, however previous reports have indicated that this risk is lower relative to other flood modes in the area (Bristol City Council, 2018).

4.2 | Fluvial flooding under a tidal influence is the predominant future flood hazard in Bristol

Although the increase in estimated EAD caused by pluvial flooding is significant (£2.5 to £4.8 million in Figure 9 and Figure 10), future flood hazard up to the 2115 time horizon in Bristol is dominated by combined tidal/ fluvial flooding. Fluvial flood EAD in the city is predicted to rise 15-fold, from £0.8 to £11.8 million (Figures 5 and 6). We attribute this to the significant increase in tidal flood hazard created by sea level rise, which is in the order of magnitude of metres, and indicates that enhanced flood management actions are required to counter this significant future threat. This finding correlates with similar literature indicating that future coastal flood risk is expected to rise significantly across a global-scale (Hallegatte et al., 2013). Further details on fluvial flooding in Bristol are also available in the draft Bristol Avon Flood Strategy, which includes an options assessment to identify the best ways to manage flood risk from the Avon.

Fluvial EAD is high, however of particular concern are damage estimates linked to high magnitude, low probability events. Even in relatively frequent events, such as the 20-year return period, we calculate over £150 million in flood damages, whereas rare extreme events such as the 200-year flood are forecast to generate approximately £500 million in flood damages (Figure 3). Damage of this magnitude indicates a need to develop urban resilience strategies, which extend beyond resisting damage to provide communities with the capacity to adapt to and recover from system shocks (Butler et al., 2014). Interventions such as distributed property resilience measures provide opportunities to enhance this capacity and so should be investigated and implemented within urban environments (Bowker, 2007; White et al., 2018). Other complementary strategies, such as hard engineering, dispersed green infrastructure and catchment management may also enhance the coping capacity of downstream areas (Fletcher et al., 2015; Schanze, 2017; Webber et al., 2019).

A limitation of our study and point of note is that the flood damages here are likely to be underestimates of the actual disruption caused during an event of this magnitude. This is because we calculate damages based on direct tangible flood damages to buildings (Hammond et al., 2015). Flooding is also likely to incur significant additional direct damages to building contents and critical infrastructure, such as transport (Evans et al., 2020; Pregnolato, Ford, Wilkinson, & Dawson, 2017), communication and energy networks (Hammond et al., 2018; Stevens et al., 2020). In turn, disruption is likely to cascade towards further indirect damages (Labaka, Hernantes, & Sarriegi, 2016; Little, 2002). Furthermore, flooding will affect the mental and physical health of communities in ways that are challenging to account for in purely monetary terms.

4.3 | Pluvial hazards are distributed across the city, whereas fluvial hazards are more concentrated

Pluvial flooding is distributed across the city, without an easily recognisable relationship to clear features such as watercourses or proximity to tidal waters. Figure 7 illustrates that every local authority super output area modelled contains some level of pluvial flood damage. This is in stark contrast to the fluvial flood damages presented in Figure 3, which show a clear relationship between fluvial flood damage and proximity to watercourses and the tidal influence of the Severn Estuary. This result is expected; however, it is noteworthy as the spatial differences in flood damages indicate that different targeting strategies will be required for each flooding mode.

Of particular note is the predominance of pluvial flooding to impact homes (Figure 8), which is in contrast to fluvial flooding, which tends to impact commercial and industrial properties (Figure 4). Our Supporting Information indicates that in the 100-year event pluvial flooding poses a risk to between 3842 (baseline) and 5144 (BAU) homes, whereas fluvial flooding risks between 16 (baseline) and 74 (BAU). This significant risk posed by pluvial flooding is evident even during lower magnitude return periods in the present-day scenario.

On the other hand, fluvial flooding is a much more concentrated hazard, which in this case affects the Harbourside area, which predominantly consists of commercial and industrial buildings. However, rising fluvial flood damage to homes in future scenarios highlights changes to flood distributions caused by increasing rainfall in the catchment coupled with rising sea levels in the Severn Estuary, result in significant alterations to typical hazards and leads to properties currently regarded as relatively safe being flooded. This emphasises the need to understand future flood risk and target effective management strategies.

4.4 | Effective resistance based PFR is dependent on hazard type and intervention distribution

Interventions reduced damage by some degree in all scenarios. When evaluated by EAD, the reduction of pluvial flood damage is generally greater than the reduction in fluvial flood damage. However, more properties are vulnerable to pluvial flooding within the top three flooded areas, and therefore a larger number of properties are treated with interventions (339 residential properties in the pluvial and 235 in the fluvial analysis); therefore, we have evaluated the per intervention effectiveness below.

4.4.1 | Hazard type: resistance based PFR is most effective at mitigating shallow pluvial flooding

When evaluated on a per property basis (Figure 11) the reduction in total EAD caused by interventions in the baseline scenario is much higher for pluvial defences, which realise between £350 (strategic area) and £1,150 (individual targeting) per implementation, whilst the average annual benefit for fluvial PFR is less than £50 per property.

However, it should be noted that interventions performance in the baseline scenario is limited due to measures being targeted based on the BAU flood extents, therefore some intervention implementations do not realise a benefit now based on future risk. This is particularly evident for fluvial flood scenarios, which experience a much greater increase in flood hazards between scenarios due to sea level rise, rather than pluvial flooding for which extent is similar between scenarios. This is demonstrated by a much greater number of residential properties flooding in the fluvial BAU 20 and 100-year events (364–990) relative to the difference between the same events in the baseline scenario (6–74; Supporting Information).

Pluvial and fluvial interventions perform similarly during the BAU scenario, with pluvial interventions realising EAD reductions of £470 and £1,240 and fluvial interventions realising £720 and £940. However, whilst pluvial flood benefit remains relatively consistent across all return periods, the majority of fluvial EAD reduction is realised during the 20-year event (Supporting Information). This is due to PFR effectiveness decreasing in extreme cases when flooding reaches or exceeds the 600 mm threshold (Bowker, 2007), demonstrated by only small reductions in fluvial damage in the BAU 200 and 1,000-year events. This highlights that resistance based PFR is most effective at managing shallow flooding, rather than deeper events. Furthermore, although outside the scope of our study, other literature also highlights that resilience and recovery based PFR can offer significant additional benefits to households where water ingress does occur (Beddoes, Booth, & Lamond, 2018).

Flooding above the resistance effectiveness threshold highlights the need for management strategies to consist of a diverse range of interventions, including property level defences for hazard resistance and resilience, complemented by dispersed catchment management measures which can mitigate hazards upstream (Schanze, 2017; Schubert et al., 2017). However, in terms of fluvial flooding exacerbated by tidal locking, this sort of upstream implementation may be insufficient to mitigate the predicted sea level rise in the order of meters. Therefore it is important that community resilience measures are implemented to provide safe management and recovery from extreme hazards and climate change mitigation strategies are implemented on a global-scale to limit the

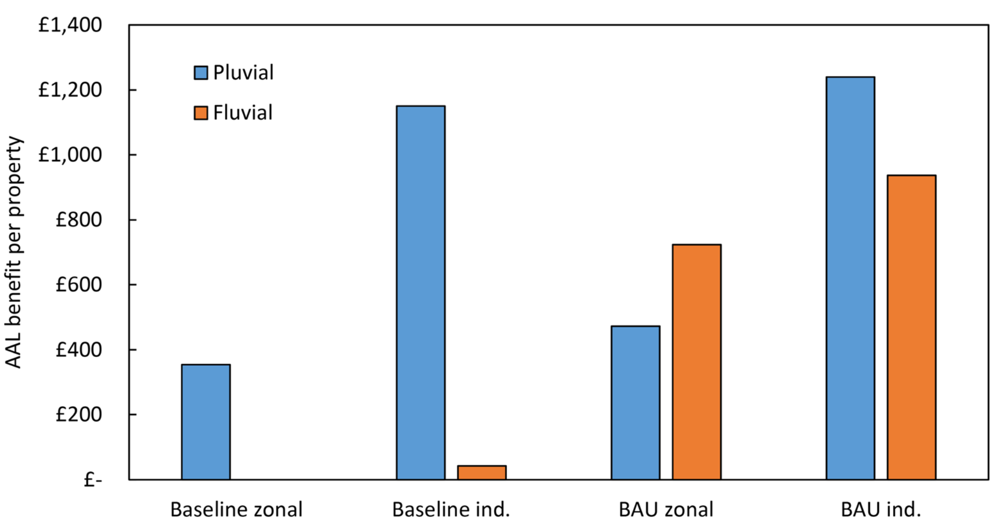

FIGURE 11 Reduction in estimated annual damage per property for all targeting strategies. Full results are available in the Supporting Information

impact of sea level rise (Butler et al., 2017; Webber, Fu, & Butler, 2019; White et al., 2018).

4.4.2 | PFR targeting strategies: individually targeted PFR is most effective, particularly for pluvial hazards

We find that individually targeting PFR is always a more effective option than focusing resources on specific high-risk areas. This finding supports current strategies for implementing PFR, where the flexibility of targeting individual properties is seen as a way of addressing risks to homes which are at a higher risk but may not benefit from community level defences (DEFRA, 2014; Lamond et al., 2018).

This is particularly significant in the case of pluvial flood management, where individually targeted PFR provides an additional average benefit of between £750 (BAU) and £800 (baseline) per property per year, versus targeting strategic areas. This significant difference is due to the extensive and varied distribution of pluvial flooding causing damages across a catchment. Therefore, focusing resources on one area is not as effective as individually targeting properties. This supports application of catchment wide high-resolution hydrodynamic modelling to evaluate and mitigate pluvial risks.

Differences in intervention targeting strategies are less noticeable for fluvial flooding, where changes in approach only represent a difference between £40 and £210 per property (baseline and BAU, respectively). This is due to the higher spatial concentration of fluvial flooding making a zonal targeting strategy similar to individual targeting. This finding supports zonal implementation of fluvial defences but indicates a need for implementing diverse management strategies capable of mitigating, resisting and adapting to deep flooding. This is evident around the world in the large engineering projects used to manage tidal and fluvial flood interactions, such as the Thames Barrier and Dutch Polder Programme (Rowland, 2012; Stijnen, Kanning, Jonkman, & Kok, 2014).

However, a drawback of an individually targeted approach is that dedicating resources to the most damaged properties also means the deepest flooding, which in the case of PFR based interventions, is more likely to exceed the 600 mm operational threshold and so may lead to more properties flooding. We observed this when evaluating pluvial flooding in this case study. In the baseline scenario, strategic areas defend 187 properties in the 30-year pluvial flood, versus 84 when individually targeting interventions (see Supporting Information). This seems to support a strategic area targeting approach. However, strategic targeting only realises a £1.39 million reduction in damage, versus £4.56 million realised by the individually targeted measures. This highlights the benefit of additional economic analysis over purely counting flooded properties.

Furthermore, this highlights that practitioners should be wary of the events used to evaluate flood damages. Targeting the most vulnerable properties may mean that defences overtop in one particular return period; however, these high-risk properties will also be defended from more frequent flooding, therefore contributing significant benefits during lower magnitude events. Thus, the total value of these interventions is underestimated due to missed benefits during frequent storms. This is demonstrated by the large increase in defended properties during lower magnitude flooding, whilst retaining a much higher avoided damage. For example, during the 10-year event the number of properties defended by strategic and individual strategies is similar (143 and 125, respectively), whereas corresponding avoided damages are £1.06 and £3.67 million. This highlights the need to base flood management actions on a range of return periods, using metrics such as EAD to capture intervention performance across a spectrum of extreme and relatively frequent floods.

Overall, we offer general guidance that strategic level and initial targeting of urban pluvial flood management requires high-resolution analysis of runoff. A similar approach provides the best outcomes for fluvial targeting; however, the hazard is more concentrated and so a zonal approach may be more acceptable.

4.5 | Utility and transferability of this economic analysis approach

This approach presents a strategic tool for evaluating placement opportunities for property-level flood management within urban catchments. We have applied the approach here to evaluate PFR, but it is also transferable across other property-scale interventions. The key advantage of the methodology is that high quality existing modelling, of a type generally available across regions with established flood management practices, is deployed as the basis of an initial intervention assessment. The damage assessment is also adaptable to any peak flood depth mapping and therefore represents utility on a global-scale. Furthermore, the approach is efficient and can be deployed to screen a range of property-based strategies to develop understanding of options in the informative preliminary stages of flood management.

A limitation of the approach is that it evaluates property-scale impacts and not spatial adjustments to hazards. Other frameworks evaluating changes to flood extent are available, but this considerably extends data and resource requirements due to the need to develop hydro-dynamic modelling (Néelz & Pender, 2013). The drawback of these detailed approaches is that reluctance for investment in them may restrict consideration of novel management strategies, such as PFR. Preliminary methodologies, such as ours, help bridge this gap by developing initial evidence supporting consideration of novel strategies.

The simplified depth-damage assessment is also representative of broad-scale values but misses nuances of damage to individual homes and their contents. In future other damage factors, both tangible (infrastructure and cascading damages) as well as intangible (health, wellbeing), should be developed (Hammond et al., 2015). Similarly, the method only employs a high-level analysis of cost–benefit, based on general guidance assuming a set ratio of 1.6 for homes protected to a 25-year standard (Thurston et al., 2008). This is sufficient for a screening study evaluating preliminary targeting, however a detailed site-by-site assessment of property suitability, capital, operational, and maintenance costs is required as the next step towards implementing promising strategies.

A further limitation is that our research solely focuses on PFR targeting strategies. In practice, PFR forms only one component of an integrated defence scheme; therefore, we recommend that future research addresses the spatial complexities of different flood defence options. It is also noteworthy that PFR is often considered as a flexible way of extending protection to properties which do not benefit from community level defences, so it is further recommended that future research evaluates the temporal opportunities of targeting PFR versus more resource intensive strategies, using different planning horizons to evaluate PFR's potential role supplementing other strategies and preventing maladaptation.

In respect of these limitations, we recommended that this methodology is applied as a screening tool to evaluate high-level opportunities and feed this into flood management frameworks as part of initial option development to inform and direct later detailed design.

4.6 | PFR should be applied on a case by case basis, with respect to limitations and residual risks

Whilst many studies highlight that PFR is an effective measure in mitigating potential flood damages when installed correctly, it is important to recognise several key limitations in application of this approach (DEFRA, 2014; Lamond et al., 2018).

The primary limitation of resistance based PFR remains the possibility of residual damages through overtopping if flood levels exceed the height of defences. This is of pertinence to our study, which focuses on resistance based PFR. It should be noted that complementary PFR which address water ingress inside of properties can be applied to enhance the recovery and resilience, managing additional risk and minimising recovery costs (DEFRA, 2012). PFR may also be unsuitable for application in specific circumstances. For example, if properties have a non-standard construction (DEFRA, 2012), if water levels exceed 600 mm (Bowker, 2007), flooding persists for extended durations (Beddoes et al., 2018) or water velocity is high (BSI, 2015).

It is also important to note that effective implementation of PFR requires property owners to manage and implement products in safe and effective manner. This requires establishing a legacy to ensure property owners continue to maintain, store, and deploy measures at appropriate times. This is at odds with alternative flood resistance measures, which are typically static and do not require ongoing public engagement. Government guidance and academic research reiterates this need for effective engagement through clear and consistent communication about the responsibilities when implementing PFR (DEFRA, 2014). In particular, guidance highlights early engagement, clear instruction avoiding technical terminology and managing expectations through using terms such as 'risk reduction', rather than 'flood prevention'. Further components of effective continued engagement in support of this legacy are timely and well communicated flood warnings and establishing trust with property owners (Owusu, Wright, & Arthur, 2015; Terpstra, 2011; White et al., 2018). It should be noted that flood warnings should arrive with sufficient time for property owners to prepare, particularly in the case of pluvial flooding which often presents rapidly.

We also highlight recent reviews on UK based PFR studies which highlight that the majority of research is focused on theoretical, as opposed to empirical studies (Lamond et al., 2018). PFR has been empirically demonstrated to perform effectively elsewhere, with notable studies in Europe (Hudson et al., 2014; Kreibich et al., 2011; Poussin, Botzen, & Aerts, 2014); however future UK research should continue to develop this evidence base from a national perspective.

With these limitations in mind, PFR should not be considered a panacea, but if correctly targeted, installed, maintained, and deployed can substantially reduce flood risks to properties and the public (DEFRA, 2014; Lamond et al., 2018).

5 | CONCLUSIONS

Our work evaluates different targeting strategies for PFR and presents a method which enhances decision support through enabling a high-resolution spatial analysis representing individual properties whilst still evaluating strategy performance at the catchment-scale. Our method is supported by data types, products and best-practices which are likely to be available across, or adaptable to, a range of international contexts where systematic and centralised flood risk management takes place. As such, it is generally replicable in the informative preliminary stages of strategy exploration; this is a pertinent factor in the context of supporting wider consideration of novel strategies, such as PFR, within flood risk management.

We find that flood damage reduction differs between PFR distribution strategies and that targeting PFR at individual properties across a catchment-scale provides more effective damage reduction than concentrated uniform application within specific 'high-risk' areas. Therefore, we recommend that property level interventions for urban flood management are targeted using high-resolution analysis of flood dynamics. We find that this is particularly important for pluvial flooding, where we identified a benefit per property of approximately £750 more than applying a zonal targeting approach, but less pronounced for fluvial targeting; where a more concentrated and predictable hazard extent means focusing on high-risk areas is more acceptable. Our findings also highlight the applicability of PFR to manage damages at specific high-risk properties which may not fall under the protection of community level defences.

Future research should enhance assessment by integrating both tangible and intangible damages, evaluating PFR measures versus other flood interventions, and developing frameworks aimed at applying the type of initial optioneering developed in this work to complement and support a suite of flood risk management tools.

ACKNOWLEDGEMENTS

This work was funded by the resilience to cope with climate change in urban areas 'RESCCUE' project (European Union Grant 700174) and the NERC South West Partnership for Environment and Economic Prosperity 'SWEEP' (NE/P011217/1). Flood damage tools were provided by the collaborative research on flood resilience in urban areas 'CORFU' project (European Union Grant 244047). The authors thank the support provided from stakeholders at Bristol City Council, Wessex Water, and Urban DNA.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

James L. Webber https://orcid.org/0000-0002-1158-4895
Albert S. Chen https://orcid.org/0000-0003-3708-3332
Slobodan Djordjević https://orcid.org/0000-0003-1682-1383
Barry Evans https://orcid.org/0000-0003-1316-2087

REFERENCES

Ana, E. V., & Bauwens, W. (2010). Modeling the structural deterioration of urban drainage pipes: The state-of-the-art in statistical methods. *Urban Water Journal*, *7*(1), 47–59. https://doi.org/10.1080/15730620903447597

Bates, P. D., Wilson, M. D., Horritt, M. S., Mason, D. C., Holden, N., & Currie, A. (2006). Reach scale floodplain inundation dynamics observed using airborne synthetic aperture radar imagery: Data analysis and modelling. *Journal of Hydrology*, *328*(1–2), 306–318. https://doi.org/10.1016/J.JHYDROL.2005.12.028

Beddoes, D. W., Booth, C. A., & Lamond, J. E. (2018). Towards complete property–level flood protection of domestic buildings in the UK. *Urban Water Systems & Floods II*, p. 184. Available from https://books.google.co.uk/books?hl=en&lr=&id=qTlpDwAAQBAJ&oi=fnd&pg=PA27&dq=beddoes+booth+flood+&ots=_WwZdRPZWi&sig=XC6Sz8iPDNsEkm0Tf3-INWBRbk#v=onepage&q=beddoes

Bowker, P. (2007). Flood resistance and resilience solutions: An R & D scoping study.

Bowker, P., Escarameia, M. & Tagg, A. 2007. Improving the flood performance of new buildings—Flood resilient construction. p. 100.

Bristol City Council. (2012) Bristo surface water management plan (phase 1). Available from www.arup.com.

Bristol City Council. (2015). Bristol central area flood risk assessment. Bristol, UK.

Bristol City Council. (2018). Bristol local flood risk management strategy.

Bristol City Council. (2019). The population of Bristol. Available from www.bristol.gov.uk/population.

BSI. (2015). BS 85500 Flood resilient construction—Guide to improving the flood performance of buildings. Available from https://standardsdevelopment.bsigroup.com/projects/9020-04770#/section.

Butler, D., Digman, C., Makropoulos, C., & Davies, J. (2018). *Urban drainage* (4th ed.). London: CRC Press.

Butler, D., Farmani, R., Fu, G., Ward, S., Diao, K., & Astaraie-Imani, M. (2014). A new approach to urban water management: Safe and sure. *Procedia Engineering*, *89*, 347–354. https://doi.org/10.1016/j.proeng.2014.11.198

Butler, D., Ward, S., Sweetapple, C., Astaraie-Imani, M., Diao, K., Farmani, R., & Fu, G. (2017). Reliable, resilient and sustainable water management: The safe & SuRe approach. *Global Challenges*, *1*(1), 63–77. https://doi.org/10.1002/gch2.1010

Carter, J. G., White, I., & Richards, J. (2009). Sustainability appraisal and fl ood risk management. *Environmental Impact Assessment Review*, *29*, 7–14. https://doi.org/10.1016/j.eiar.2008.06.003

Chen, A., Hammond, M., Djordjević, S., Butler, D., Khan, D. M., & Veerbeek, W. (2016). From hazard to impact: Flood damage assessment tools for mega cities. *Natural Hazards*, *82*(2), 857–890.

Available from https://link.springer.com/article/10.1007/s11069-016-2223-2

Chen, A. S., Djordjević, S., Leandro, J., & Savić, D. A. (2010). An analysis of the combined consequences of pluvial and fluvial flooding. *Water Science and Technology*, *62*(7), 1491–1498. https://doi.org/10.2166/wst.2010.486

Chen, A. S., Evans, B., Djordjević, S., & Savić, D. A. (2012). A coarse-grid approach to representing building blockage effects in 2D urban flood modelling. *Journal of Hydrology*, *426–427*, 1–16. https://doi.org/10.1016/J.JHYDROL.2012.01.007

Commitee on Climate Change. (2015). Progress in preparing for climate change. Available from www.theccc.org.uk.

Committee on Climate Change. (2017). UK climate change risk assessment 2017 synthesis report. Available from https://www.theccc.org.uk/wp-content/uploads/2016/07/UK-CCRA-2017-Synthesis-Report-Committee-on-Climate-Change.pdf.

DCLG. (2010). Planning policy statement 25: Development and flood risk.

DEFRA. (2009). UK climate projections 2009. Available from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69257/pb13274-uk-climate-projections-090617.pdf.

DEFRA. (2010). Surface water management plan technical guidance.

DEFRA. (2012). Establishing the cost effectiveness of property flood protection (FD2657). Available from http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=18119.

DEFRA. (2014). Best practice in property level protection systems advice for local authorities. Available from www.gov.uk/defra.

DEFRA 2018 Surface water management: An action plan. Available from www.nationalarchives.gov.uk/doc/open-government-licence/version/3/oremailpsi@nationalarchives.gsi.gov.ukwww.gov.uk/defra.

Djordjević, S., Butler, D., Gourbesville, P., Mark, O., & Pasche, E. (2011). New policies to deal with climate change and other drivers impacting on resilience to flooding in urban areas: The CORFU approach. *Environmental Science & Policy*, *14*(7), 864–873. https://doi.org/10.1016/j.envsci.2011.05.008

Dottori, F., Di Baldassarre, G., & Todini, E. (2013). Detailed data is welcome, but with a pinch of salt: Accuracy, precision, and uncertainty in flood inundation modeling. *Water Resources Research*, *49*(9), 6079–6085. https://doi.org/10.1002/wrcr.20406

Elliott, A. H., & Trowsdale, S. A. (2007). A review of models for low impact urban stormwater drainage. *Environmental Modelling and Software*, *22*(3), 394–405. https://doi.org/10.1016/j.envsoft.2005.12.005

Environment Agency. (2007). Cost-benefit of SUDS Retrofit in Urban Areas (Report SC060024). Available from http://publications.environment-agency.gov.uk/PDF/SCHO0408BNXZ-E-E.pdf.

Environment Agency. (2014). National receptor database.

Environment Agency. (2015a). Cost estimation for household flood resistance and resilience measures-summary of evidence. Available from www.gov.uk/government/publications.

Environment Agency. (2015b). Cost estimation for SUDS—Summary of evidence (Report SC080039/R9). Available from www.environment-agency.gov.uk.

Evans, B., Chen, A. S., Djordjević, S., Webber, J., Gómez, A. G., & Stevens, J. (2020). Investigating the effects of pluvial flooding and climate change on traffic flows in Barcelona and Bristol. *Sustainability*, *12*(6), 2330. https://doi.org/10.3390/su12062330

Fenner, R. A. (2000). Approaches to sewer maintenance: A review. *Urban Water*, *2*, 343–356 Available from www.elsevier.com/locate/urbwat

Fewtrell, T. J., Duncan, A., Sampson, C. C., Neal, J. C., & Bates, P. D. (2011). Benchmarking urban flood models of varying complexity and scale using high resolution terrestrial LiDAR data. *Physics and Chemistry of the Earth, Parts A/B/C. Pergamon*, *36*(7–8), 281–291. https://doi.org/10.1016/J.PCE.2010.12.011

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., … Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, *12*(7), 525–542. https://doi.org/10.1080/1573062X.2014.916314

Golz, S., Schinke, R., & Naumann, T. (2015). Assessing the effects of flood resilience technologies on building scale. *Urban Water Journal*, *12*(1), 30–43. https://doi.org/10.1080/1573062X.2014.939090

Guerreiro, S. B., Dawson, R. J., Kilsby, C., Lewis, E., & Ford, A. (2018). Future heat-waves, droughts and floods in 571 European cities. *Environmental Research Letters*, *13*(3), 034009. https://doi.org/10.1088/1748-9326/aaaad3

Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nature Climate Change*, *3*(9), 802–806. https://doi.org/10.1038/nclimate1979

Hammond, M., Chen, A. S., Batica, J., Butler, D., Djordjević, S., Gourbesville, P., … Veerbeek, W. (2018). A new flood risk assessment framework for evaluating the effectiveness of policies to improve urban flood resilience. *Urban Water Journal*, *15*(5), 427–436. https://doi.org/10.1080/1573062X.2018.1508598

Hammond, M. J., Chen, A. S., Djordjević, S., Butler, D., & Mark, O. (2015). Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, *12*(1), 14–29. https://doi.org/10.1080/1573062X.2013.857421

HM Government. (2010). Flood and water management act 2010. Available from http://www.legislation.gov.uk/ukpga/2010/29/pdfs/ukpga_20100029_en.pdf.

Hudson, P., Botzen, W., Kreibich, H., Bubeck, P., Botzen, W. J. W., & Aerts, J. C. J. H. (2014). Evaluating the effectiveness of flood damage mitigation measures by the application of propensity score matching. *Natural Hazards and Earth System Sciences*, *14*, 1731–1747. https://doi.org/10.5194/nhess-14-1731-2014

Hunter, N. M., Bates, P. D., Neelz, S., Pender, G., Villanueva, I., Wright, N. G., … Mason, D. C. (2008). Benchmarking 2D hydraulic models for urban flooding. *Proceedings of the Institution of Civil Engineers - Water Management*, *161*(1), 13–30. https://doi.org/10.1680/wama.2008.161.1.13

Hyder Consulting. (2013). Bristol central area flood risk assessment-summary report. Available from http://www.environment-agency.gov.uk/research/planning/114342.aspx.

Ingargiola, J. L., Jones, C. P., & Quinn, R. C. (2012). Improving the performance of buildings and structures in flood hazard areas. In *Advances in hurricane engineering* (pp. 53–66). Reston, VA:

American Society of Civil Engineers. https://doi.org/10.1061/9780784412626.006

IPCC. (2014). *Climate Change 2014*: *Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Jasanoff, S., & Wynne, B. (1998). Science and decision making. In S. Raynor & E. L. Malone (Eds.), *Human choice and climate change, Vol. 1. The societal framework*. Columbus, OH: *Batelle Institute*.

Jayasooriya, V. M., & Ng, A. W. M. (2014). Tools for modeling of Stormwater management and economics of Green infrastructure practices: A review. *Water, Air, & Soil Pollution*, *225*(8), 2055. https://doi.org/10.1007/s11270-014-2055-1

Kreibich, H., Seifert, I., Thieken, A. H., Lindquist, E., Wagner, K., & Merz, B. (2011). Recent changes in flood preparedness of private households and businesses in Germany. *Regional Environmental Change*, *11*(1), 59–71. https://doi.org/10.1007/s10113-010-0119-3

Labaka, L., Hernantes, J., & Sarriegi, J. M. (2016). A holistic framework for building critical infrastructure resilience. *Technological Forecasting and Social Change*, *103*, 21–35. https://doi.org/10.1016/j.techfore.2015.11.005

Lamond, J., Rose, C., Bhattacharya-Mis, N. & Joseph, R. (2018). Evidence review for property flood resilience. Available from https://uwe-repository.worktribe.com/output/874824.

Little, R. (2002). Controlling cascading failure: Understanding the vulnerabilities of interconnected infrastructures*. *Journal of Urban Technology*, *9*(1), 109–123. https://doi.org/10.1080/106307302317379855

Merz, B., Kreibich, H., Schwarze, R., & Thieken, A. (2010). Review article "assessment of economic flood damage". *Natural Hazards and Earth System Science.*, *10*, 1697–1724. https://doi.org/10.5194/nhess-10-1697-2010

Merz, B., Kreibich, H., Thieken, A., & Schmidtke, R. (2004). Estimation uncertainty of direct monetary flood damage to buildings. *Natural Hazards and Earth System Science*, *4*(1), 153–163. https://doi.org/10.5194/nhess-4-153-2004

Mignot, E., Paquier, A., & Haider, S. (2006). Modeling floods in a dense urban area using 2D shallow water equations. *Journal of Hydrology*, *327*(1–2), 186–199. https://doi.org/10.1016/J.JHYDROL.2005.11.026

Néelz S. & Pender G. 2013 Delivering benefits thorough evidences: Benchmarking the latest generation of 2D hydraulic modelling packages (report-SC120002).

O'Donnell, E. C., Lamond, J. E., & Thorne, C. R. (2017). Recognising barriers to implementation of blue-Green infrastructure: A Newcastle case study. *Urban Water Journal*, *14*(9), 964–971. https://doi.org/10.1080/1573062X.2017.1279190

Ordnance Survey 2020 OS digimap service. Available from https://digimap.edina.ac.uk/.

Owusu, S., Wright, G., & Arthur, S. (2015). Public attitudes towards flooding and property-level flood protection measures. *Natural Hazards*, *77*(3), 1963–1978. https://doi.org/10.1007/s11069-015-1686-x

Penning-Rowsell, E., Viavattene, C. & Parode, J. (2010). The benefits of flood and coastal risk management: A handbook of assessment Techniques-2010 (multi-coloured manual). *Flood Hazard Research*.

Pitt, M. (2008). The Pitt review: Learning lessons from the 2007 floods.

Poussin, J. K., Botzen, W. J. W., & Aerts, J. C. J. H. (2014). Factors of influence on flood damage mitigation behaviour by households. *Environmental Science and Policy*, *40*, 69–77. https://doi.org/10.1016/j.envsci.2014.01.013

Pregnolato, M., Ford, A., Wilkinson, S. M., & Dawson, R. J. (2017). The impact of flooding on road transport: A depth-disruption function. *Transportation Research Part D: Transport and Environment*, *55*, 67–81. https://doi.org/10.1016/j.trd.2017.06.020

Rowland, D.. (2012). Climate change risk assessment for the floods and coastal erosion sector. (January).

Schanze, J. (2017). Nature-based solutions in flood risk management - Buzzword or innovation? *Journal of Flood Risk Management*, *10*(3), 281–282. https://doi.org/10.1111/jfr3.12318

Schubert, J. E., Burns, M. J., Fletcher, T. D., & Sanders, B. F. (2017). A framework for the case-specific assessment of Green infrastructure in mitigating urban flood hazards. *Advances in Water Resources*, *108*, 55–68. https://doi.org/10.1016/J.ADVWATRES.2017.07.009

Schubert, J. E., & Sanders, B. F. (2012). Building treatments for urban flood inundation models and implications for predictive skill and modeling efficiency. *Advances in Water Resources*, *41*, 49–64. https://doi.org/10.1016/J.ADVWATRES.2012.02.012

Shah, M. A. R., Rahman, A., & Chowdhury, S. H. (2018). Challenges for achieving sustainable flood risk management. *Journal of Flood Risk Management*, *11*, 352–358. https://doi.org/10.1111/jfr3.12211

Stevens, J., Henderson, R., Webber, J., Evans, B., Chen, A., Djordjević, S., … Domínguez-García, J. (2020). Interlinking Bristol based models to build resilience to climate change. *Sustainability*, *12*(8), 3233. https://doi.org/10.3390/su12083233

Stijnen, J. W., Kanning, W., Jonkman, S. N., & Kok, M. (2014). The technical and financial sustainability of the Dutch polder approach. *Journal of Flood Risk Management*, *7*(1), 3–15. https://doi.org/10.1111/jfr3.12022

Syme, W., Pinnell, M. & Wicks, J. (2004). Modelling flood inundation of urban areas in the UKusing 2D/1D hydraulic models. The Institution of Engineers, Australia 8th National Conference on Hydraulics in Water Engineering. Gold Coast, Australia. Available from http://www.tuflow.com/Download/Publications/Modelling.

Terpstra, T. (2011). Emotions, trust, and perceived risk: Affective and cognitive routes to flood preparedness behavior. *Risk Analysis*, *31*(10), 1658–1675. https://doi.org/10.1111/j.1539-6924.2011.01616.x

Thorne, C. R., Lawson, E. C., Ozawa, C., Hamlin, S. L., & Smith, L. A. (2018). Overcoming uncertainty and barriers to adoption of blue-Green infrastructure for urban flood risk management. *Journal of Flood Risk Management*, *11*(11), S960–S972. https://doi.org/10.1111/jfr3.12218

Thurston, N., Finlinson, B., Breakspear, R., Williams, N., Shaw, J. & Chatterton, J. (2008). Developing the evidence base for flood resistance and resilience: Summary report. Defra, pp. 1–20.

UK Government. (2020). Flood risk assessments: Climate change allowances—GOV.UK. Available from https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances.

University of Exeter. (2014). Flood damage model guidelines. CORFU project (WP3 output).

US Army Corps of Engineers. (1988). Flood proofing tests—Tests of materials and systems for floodproofing structures.

Velasco, M., Russo, B., Martínez, M., Malgrat, P., Monjo, R., Djordjevic, S., … Buskute, A. (2018). Resilience to cope with climate change in urban areas—A multisectorial approach focusing on water—The RESCCUE project. *Water*, *10*(10), 1356. https://doi.org/10.3390/w10101356

Viavattene, C., & Ellis, J. B. (2013). The management of urban surface water flood risks: SUDS performance in flood reduction from extreme events. *Water Science and Technology*, *67*(1), 99–108. https://doi.org/10.2166/wst.2012.537

Webber, J. L., Fletcher, T. D., Cunningham, L., Fu, G., Butler, D., & Burns, M. J. (2019). Is green infrastructure a viable strategy for managing urban surface water flooding? *Urban Water Journal*, *17*, 1–11. https://doi.org/10.1080/1573062X.2019.1700286

Webber, J. L., Fu, G., & Butler, D. (2019). Comparing cost-effectiveness of surface water flood management interventions in a UK catchment. *Journal of Flood Risk Management*, *12*(S2), e12523. https://doi.org/10.1111/jfr3.12523

White, I., Connelly, A., Garvin, S., Lawson, N., & O'Hare, P. (2018). Flood resilience technology in Europe: Identifying barriers and co-producing best practice. *Journal of Flood Risk Management*, *11*, S468–S478. https://doi.org/10.1111/jfr3.12239

Wing, O. E. J., Bates, P. D., Smith, A. M., Sampson, C. C., Johnson, K. A., Fargione, J., & Morefield, P. (2018). Estimates of present and future flood risk in the conterminous United States. *Environmental Research Letters*, *13*(3), 034023. https://doi.org/10.1088/1748-9326/aaac65

Wong, T. H. & Eadie, M. L. (2000). *Water Sensitive Urban Design*: *A Paradigm Shift in Urban Design*. 10th World Water Congress: Water, The Worlds Most Important Resource. International Water Resources Association, p. 1281. Available from https://search.informit.com.au/documentSummary;dn=519426635188728;res=IELENG.

Wong, T. H. F., & Brown, R. R. (2009). The water sensitive city: Principles for practice. *Water Science and Technology*, *60*(3), 673–682. https://doi.org/10.2166/wst.2009.436

Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., & Kellagher, R. (2015). *The SuDS manual (C753)*. London, UK: CIRIA.

Yu, D., & Lane, S. N. (2006). Urban fluvial flood modelling using a two-dimensional diffusion-wave treatment, part 1: Mesh resolution effects. *Hydrological Processes*, *20*(7), 1541–1565. https://doi.org/10.1002/hyp.5935

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Webber JL, Chen AS, Stevens J, Henderson R, Djordjević S, Evans B. Targeting property flood resilience in flood risk management. *J Flood Risk Management*. 2021; e12723. https://doi.org/10.1111/jfr3.12723