Drivers of Future Urban Flood Risk

Emily C. O'Donnell[1]* and Colin R. Thorne[1]

[1]School of Geography, University of Nottingham, Nottingham, NG7 2RD, UK
*corresponding author (Emily.O'Donnell@nottingham.ac.uk)

EO: 0000-0003-4303-4705, CT: 0000-0002-2450-9624

Keywords:

Urban Flooding; Flood Foresight; Extreme Rainfall; Climate Change; Source-pathway-receptor model; Flood risk scenario modelling

Abstract

Managing urban flood risk is a key global challenge of the 21st Century. Drivers of future UK flood risk were identified and assessed by the Flood Foresight project in 2002-04 and 2008; envisaging flood risk during the 2050s and 2080s under a range of scenarios for climate change and socio-economic development. This paper qualitatively reassesses and updates these drivers, using empirical evidence and advances in flood risk science, technology and practice gained since 2008. Of the original drivers, five have strengthened, three have weakened and 14 remain within their 2008 uncertainty bands. Rainfall, as impacted by climate change, is the leading source driver of future urban flood risk. Intra-urban Asset Deterioration, leading to increases in a range of consequential flood risks, is the primary pathway driver. Social impacts (risk to life and health, and the intangible impacts of flooding on communities) and continued capital investment in Buildings and Contents (leading to greater losses when newer buildings of higher economic worth are inundated), have strengthened as receptor drivers of urban flood risk. Further, we propose two new drivers: Loss of Floodable Urban Spaces, and Indirect Economic Impacts, which we suggest may have significant impacts on future urban flood risk.

1. Background

Urban flooding is one of the key global challenges of the 21st Century, with future flood risk being exacerbated by climate change, urbanisation and ageing infrastructure. By 2050, 68% of the world's population is expected to reside in cities [1], elevating flood risk to people, property and critical infrastructure systems, including transport, communications and energy, and increasing pressure on already overburdened drainage and water management infrastructure. In the UK, the 2017 Climate Change Risk Assessment reports that flooding and coastal change risks to communities, businesses and infrastructure is one of the top six areas of inter-related climate change risks [2].

Six of the ten wettest years in the UK, in a record dating from 1862, have occurred since 1998, and between 2009 and 2018, UK winters have been, on average, 12% wetter than between 1981 and 2010 [3]. Recent UK Climate Projections (UKCP18) suggest milder, wetter winters and hotter, drier summers featuring increases in the frequency and intensity of extreme weather events, including intense rainfall that leads to (pluvial) surface water/flash flooding [3]. Increased rainfall is particularly significant because 3.2 million of the 5.2 million properties in England that are at significant risk of flooding, are at risk from surface water flooding [4].

Flood risk is further exacerbated by increased urbanisation that reduces permeable green space and builds on floodplains. Urban environments are particularly vulnerable to flooding driven by heavy rainfall, which as noted above, has become increasingly frequent in the UK during the last decade [5]: e.g. Cumbria November 2009 [6], June 2012 supercell thunderstorms [7], 2013/2014 and 2015/2016 winter floods [8, 9], and many examples of localised flooding, e.g. in Lincolnshire and Kent caused by an 'exceptionally wet June' in 2019 [10]. Also, the 2013/2014 and 2015/2016 UK floods illustrate an increase in 'coincident flooding'; where sequences and clusters of individual events involving different combinations of rainfall, tidal, river and groundwater sources lead to widespread and prolonged flooding [8].

In light of these events, and other developments during the last decade, this paper qualitatively reassesses and updates the drivers of future flood risk identified in the Foresight project on Flood and Coastal Defence that reported its findings in 2004 and 2008 [11, 12]. Driver intensity and direction of change are re-evaluated using evidence, research and scientific advances that have become available since 2008, focusing on the urban flooding system. The review is general in its approach, covering the whole of the UK and using examples of recent flood events to provide supporting evidence for driver change, where applicable. *Drivers* are defined as phenomena that may change the state of the flooding system, and are classified according to the Source-Pathway-Receptor framework (Figure S1). *Drivers* rarely influence the flooding system in isolation; usually, changes in flood risk result from interactions between drivers, e.g. socio-economic drivers influence the type and rate of urbanisation to change pluvial flood risk, while surges combine with relative Sea-Level Rise to alter the magnitude and frequency of extreme, high coastal water levels. Changes to the flooding system that are implemented to reduce flood risk are categorised as *Responses* and are not updated here, given our focus on *Drivers*. That said, we acknowledge that the distinction between drivers and responses is not always clear; for example, poorly planned or implemented responses may become drivers, and drivers that are influenced by flood risk management can act as responses when managed appropriately [11].

In the Flood Foresight studies of 2002-04 and 2008, four socio-economic scenarios were used to represent a range of possible futures, expressed in terms of variation in governance and societal values, demographics and settlement patterns, political change, and economic growth. In the 2002-04 study, these socio-economic futures were associated with the then current Intergovernmental Panel on Climate Change (IPCC) climate change scenarios; World Markets (High emissions); National Enterprise (Medium-High emissions); Local Stewardship (Medium-Low emissions); and Global Sustainability (Low emissions) (Table S1 and Figure S2). Future flood risks for each of the drivers under the four scenarios were expressed as multipliers of 2002-04 flood risks, with their values being assessed by a panel of experts. These flood risk multipliers were then used to rank the drivers under each scenario, for the 2050s and 2080s. In the 2008 Flood Foresight update, these scenarios were reviewed, based on events between 2004 and 2008, and the IPCC fourth assessment report (AR4) [13].

Updating the socio-economic and climate change scenarios, and using the outcomes to derive new scenario-based driver rankings, would require assembling a new panel of experts and investment in supporting their work over a period of months, which is beyond the scope of this review. Instead, we review the drivers qualitatively, to ascertain whether they have strengthened, weakened or remained within the uncertainty bands allocated to them in 2008. However, we strongly recommend that the drivers of future flood risk are fully re-assessed in 2020, to account for radical changes that either have occurred since 2008, or which are about to occur, e.g. UKCP18 climate change projections [14] and near-term changes to flood risk management, social, economic, agricultural, planning and environmental policies, post-Brexit.

2. River, Coastal and Intra-urban Drivers in the original Flood Foresight Study (2002-2004)

In the UK, research aimed at identifying, assessing and, where possible, quantifying drivers responsible for increases in future flood risk began in response to the Millennium floods. Following a prolonged, relatively flood-free period between the late-1950s and the late-1990s, serious flooding in 1998 was characterised as an exceptional event that was unlikely to recur, with the heavy damages it caused being attributed to “unsatisfactory planning, inadequate warnings for the public, incomplete defences, and poor co-ordination with emergency services" [15]. When national-scale flooding recurred only two years later, John Prescott (then Deputy Prime Minister, DPM) linked this directly to climate change, describing the Millennium floods as, "a wake-up call" and predicting that, "these incidents are not infrequent and are going to be more frequent".

In response to the DMP's prescient remarks, Sir David King (then HM Government's Chief Scientific Advisor) asked the Office of Science and Technology to "use the best available science to provide a challenging vision for flood and coastal defence in the UK between 2030 and 2100 and so inform long-term policy". The result was the Foresight Project on Flood and Coastal Defence, which reported its findings in 2004 [12].

The approach adopted by Flood Foresight was to envisage what flooding could look like in the 2050s and 2080s under a range of possible scenarios for climate change and socio-economic development. This was necessary to allow Government to develop policies with the capacity to adapt flexibly as the future unfolds. Flood Foresight used four pre-existing scenarios embodying different approaches to governance (centralised versus localised) and different values held by society (consumerist versus community) (Figure S2, Table S1). They associated each of these socio-economic scenarios with an appropriate future climate change scenario, drawn from those reported by the IPCC [16].

In envisaging how flooding and its impacts might change between 2030 and 2100, Flood Foresight adopted a 'baseline assumption' that existing policies and annual expenditures on flood risk management would remain unchanged: in terms of flood risk management, the future would be 'business as usual'. This was essential in order to discern how future flood risks might change if rising flood risk was ignored and appropriate responses were not implemented.

In the original Flood Foresight study, drivers of broad-scale, river and coastal flooding were treated separately from those operating within urban areas. Catchment and coastal drivers were grouped into five sets on the basis of the way the drivers function and interact (Table S2). Intra-urban drivers of surface water and sewer flooding originating within urban areas were grouped into a further five driver sets, on a similar basis (Table S3).

This paper focuses on future urban flood risks. However, it is important to recognise that the impacts of drivers of river and coastal flooding identified in the original Flood Foresight study were disproportionately large in urban areas, compared with peri-urban and rural areas. This is clear from inspection of maps showing the outcomes of quantitative evaluation of future, river and coastal flood risks performed using the Risk Assessment for Strategic Planning (RASP) tool (Figure S3). Inspection of the spatial distributions of Average Annual Expected Damages (AAEDs) due to river and coastal flooding in the 2080s reveal that the highest increases in risk (represented by the darker red colours) coincide with urban conurbations, even though the impacts of intra-urban drivers were not included in the 2002-2004 RASP analysis. While the monetised values of AAEDs calculated using RASP have subsequently been challenged as exaggerating the true costs of UK flooding [17], this does not affect the relative increases in AAEDs mapped by Flood Foresight.

The original Flood Foresight study did not evaluate future intra-urban flood risks quantitatively due to high uncertainties and the then limited capacity to model surface water and sewer flooding. However, a panel of experts was able to score and rank the intra-urban drivers, based on best estimates of the multipliers of future versus current (2002) intra-urban flood risks. Intra-urban flood risk multipliers are listed in Table S4 and the drivers are ranked in Table S5. Recognising lack of knowledge concerning the intra-urban drivers, uncertainty bands were assigned to the drivers (Table S6).

3. Urban Drivers in the Foresight Update 2008

The original Flood Foresight report was updated in 2008 [11] using evidence and research that had become available since 2004, including data and insights from the summer 2007 floods, when exceptional rainfall caused unprecedented flooding of communities and infrastructure in South and East Yorkshire, Worcestershire, Gloucestershire and Oxfordshire [18]. Scenarios for climate change and socio-economic development were revisited and a high-level, evidence-based, qualitative analysis was conducted to re-evaluate the original drivers and determine whether a) any additional drivers had emerged; b) new/better data had significantly changed the assessment of the drivers and their contribution to future flood risk, and c) their risk ranking relative to the other drivers had changed.

In the 2008 study, in order to tackle flood risk more effectively and, in particular, to address the risks associated with coincident flooding, a more holistic, integrated approach to flood management was deemed imperative. This acknowledged the recommendations made by the Pitt Review [18] and Defra's *Making Space for Water* delivery plan [19]. Hence, fluvial, coastal and intra-urban drivers were combined into a single list (**Error! Reference source not found.**) and set of ranking tables (**Error! Reference source not found.** illustrates the driver ranking tables for the 2050s; Table S7 shows the driver rankings for the 2080s). One new driver set (Groundwater Systems and Processes) was added, and one driver set (Public Attitudes and Expectations) was moved to the *Responses* section, where it was deemed to be better placed as an indirect driver of flood risk based on public reactions to flood risks and management strategies.

Updating the drivers led to several key conclusions. Climate change drivers were found to be the strongest drivers of risk among physical processes. Rainfall, in particular, was recognised as a major driver that had strengthened since 2004. Overall, the impact of the new groundwater flooding driver was regarded as low owing to the potential for risk to decrease under hotter, drier high emission climate change scenarios being offset by potential increases under cooler temperatures and lower emissions. Better science and understanding of driver impacts led to an increase in the future risk of flooding from fluvial sources. The effectiveness of the sewerage systems was regarded as a key driver, as were the social and economic choices made by communities and their elected representatives. The biggest driver of economic flood risk remained impacts of infrastructure loss, echoing the 2004 report.

Flood risk multipliers were then calculated for each of the drivers under each of the four scenarios, at local and national level, and assessed relative to the 'business as usual', baseline assumption (e.g. see Table S8 for driver impact on local flood risk). The 2008 multipliers were compared with those calculated in 2004 and significant changes in multipliers were highlighted, e.g. precipitation increased in importance as a driver under the World Markets and National Enterprise scenarios, and the agricultural impacts driver increased under all scenarios owing to greater pressure on land and agricultural commodity prices (Table S8). The updated flood risk multipliers were then used to re-rank the drivers, as illustrated for the 2050s, in Table 2. Revised uncertainty bands were also assigned to the drivers (Table S9 and S10).

4. Future Drivers of Urban Flood Risk

Empirical evidence and advances in scientific knowledge, techniques and practice were used to qualitatively update the 2008 Flood Foresight drivers of combined fluvial/coastal and intra-urban flood risk, and infer how they have changed during the last decade. Drivers are stated to have strengthened or weakened only if our analyses suggest that they had changed sufficiently to move outside of their 2008 uncertainty bands, which constitutes a significant change. The drivers were assessed under the baseline assumption that current levels of expenditure and approaches to flood risk management remain unchanged.

It is acknowledged that the future intensity of drivers will vary between the four scenarios for climate change and socio-economic development. However, to attempt to account for inter-scenario variability would be a major task that is beyond the scope of this study. Hence, only overarching changes to the intensities of the drivers are listed in **Error! Reference source not found.**. In summary, five drivers have strengthened, three have weakened and 14 remain within their uncertainty bands. The Science and Technology driver was not scored in the 2008 study; therefore, we do not comment on its change in intensity. Two new drivers have been identified and added to the original 23: Loss of Floodable Urban Spaces (a pathway driver in the Urban Systems and Processes set), and, Indirect Economic Impacts (a receptor driver in the Socio-economics set) (**Error! Reference source not found.**). We now briefly report the reasoning behind our re-assessment of the direction and significance of change in each of the drivers.

Table 1 Combined list of fluvial/coastal and intra-urban drivers of future flood risk based on the drivers identified in Evans et al., (2004, 2008) and including two new drivers for 2019: Urban Systems and Processes: Loss of Urban Green Space, and Socio-economics: Indirect Economic Impacts. Driver groups are classified according to the Source (S) – Pathways (P) – Receptor (R) model of the flooding system. *New drivers for 2019.

Driver group	Driver	Explanation
Climate Change (S)	Precipitation	Changes in short duration precipitation – amount, intensity, duration, location, seasonality and clustering.
	Temperature	Influence of temperature on soil moisture and hence runoff.
	Relative Sea-Level Rise	Rising relative Sea-Level due to climate change-induced melting of ice caps and thermal expansion in conjunction with land subsidence or uplift. Makes coastal flooding more frequent.
	Waves	Increases in the height and direction of coastal waves will transmit more wave energy to the shoreline at some locations and less energy at others, increasing the risks that waves will breach and overtop coastal defences.
	Storm surges	Increases in surge levels are expected due to climate change induced increases in storminess. Stronger surges mean that higher extreme water levels with more energy reach the shoreline, increasing risks of breaching or overtopping of coastal defences
Catchment Runoff (P)	Urbanisation	A change in land management with green field and previous surfaces covered by less-pervious materials (buildings and infrastructure) and associated new conveyance systems.
	Rural Land Management	Changes in the management of land adjacent to the urban area that influence runoff into the urban area, for example, muddy floods.
Groundwater Systems and Processes (P)	Groundwater Flooding	Groundwater flooding occurs when the water table reaches the elevation of the land surface (waterlogging) or by the emergence of water originating from sub-surface permeable strata.
Fluvial Systems and Processes (P)	Environmental Regulation	Future legislation intended to increase biodiversity and habitat protection may influence policy on flood management, with implications for river and floodplain morphology, vegetation, conveyance, and flood storage.
	River Morphology and Sediment Supply	Changes in river channel morphology (size and shape) and sediment supply that alter attributes of the river channel and floodplain to influence flood conveyance, routing and storage.
	River Vegetation and Conveyance	Vegetation and micro-morphology influence velocity distributions and turbulence levels in flows significantly. Hence, changes may affect flood conveyance.
Urban Systems and Processes (P)	Urbanisation and Intra-urban Runoff	A change in land management with green field and pervious surfaces covered by less pervious materials (buildings and infrastructure) and associated conveyance systems.
	Sewer Conveyance, Blockage and Sedimentation	Processes associated with aboveground, overland surface flow and manmade, below-ground drainage systems; including performance, maintenance and operation.
	Impact of External Flooding on Intra-urban Drainage Systems	Loss of conveyance and serviceability in below-ground drainage systems due to flooding from external sources.
	Intra-urban Asset Deterioration	Changes in performance, condition and serviceability of urban drainage assets (ageing, performance, wear and tear, and rehabilitation management).
	Loss of Floodable Urban Spaces*	Loss of urban spaces that previously helped reduce flood risk through infiltration, attenuation or storage. Includes the loss of urban green space and brownfield land (to buildings and infrastructure) and changes in the types of urban green space that affect its rainfall-runoff reduction potential.
Coastal Processes (P)	Coastal Morphology and Sediment Supply	Changes in the near-shore sea-bed, shoreline and adjacent coastal land, coastal inlets and estuaries will in the short term affect the wave and surge energies that affect the shoreline.
Human Behaviour (P)	Stakeholder Behaviour	The behaviour of individuals, groups and institutions will influence flood risk. Different mechanisms will accommodate different stakeholders' interests.
Socio-economics (R)	Buildings and Contents	The damage to domestic and commercial buildings and their contents.
	Urban Impacts	Changes in the way in which urban areas are managed and urbanisation is effected, and how planning and management may change climate- and social-change effects.
	Infrastructure Impacts	The relationship between flood risks and the array of networks and nodes that deliver physical services including gas, water, electricity, transport, telecoms, etc.
	Agricultural Impacts	The impact of flooding and associated high water tables on farm and forestry land, and managed habitats.
	Social Impacts	The risks to life and health, and the intangible impacts of flooding on people and their communities, recognising that some sections of society are more vulnerable than others.

	Indirect Economic Impacts*	The indirect impacts of flood events including losses from capital and labour productivity disruptions, e.g. flooded roads interrupting transportation and consequentially disrupting economic activities.
	Science and Technology	Application and design of the outputs of scientific and technological research.

Table 2 Updated national ranking of drivers from the 2008 Flood Foresight report, graded by national flood risk multiplier – 2050s. Driver impact category key: orange (high increase, risk multiples of more than 2), white (medium increase, multiplies between 1.2 and 2), green (low impact, multipliers between 1.0 and 1.2), purple (medium decrease, between 1.0 and 0.5), pink (high decrease, less than 0.5). Source: Evans et al., (2008).

	World Markets	National Enterprise	Local Stewardship	Global Sustainability
1	Social Impacts	Infrastructure Impacts	Social Impacts	River Vegetation and Conveyance
2	Infrastructure Impacts	Buildings and Contents	Precipitation	Social Impacts
3	Precipitation	Precipitation	River Morphology and Sediment Supply	Environmental Regulation
4	Buildings and Contents	Social Impacts	Relative Sea-Level Rise	River Morphology and Sediment Supply
5	Intra-urban Asset Deterioration	Urbanisation	Coastal Morphology and Sediment Supply	Infrastructure Impacts
6	Surges	Relative Sea-Level Rise	River Vegetation and Conveyance	Precipitation
7	Relative Sea-Level Rise	Coastal Morphology and Sediment Supply	Impact of External Flooding on Intra-urban Drainage Systems	Relative Sea-Level Rise
8	Coastal Morphology and Sediment Supply	Intra-urban Asset Deterioration	Surges	Buildings and Contents
9	Urbanisation	Surges	Environmental Regulation	Coastal Morphology and Sediment Supply
10	Stakeholder Behaviour	Urban Impacts	Infrastructure Impacts	Intra-urban Asset Deterioration
11	Waves	Waves	Intra-urban Runoff	Urban Impacts
12	Sewer Conveyance, Blockage and Sedimentation	Rural Land Management	Agricultural Impacts	Agricultural Impacts
13	Urban Impacts	Intra-urban Runoff	Temperature	Groundwater Flooding
14	Intra-urban Runoff	Sewer Conveyance, Blockage and Sedimentation	Waves	Temperature
15	Impact of External Flooding on Intra-urban Drainage Systems	Impact of External Flooding on Intra-urban Drainage Systems	Sewer Conveyance, Blockage and Sedimentation	Waves
16	Rural Land Management	Agricultural Impacts	Intra-urban Asset Deterioration	Surges
17	River Morphology and Sediment Supply	Temperature	Urban Impacts	Intra-urban Runoff
18	River Vegetation and Conveyance	River Morphology and Sediment Supply	Groundwater Flooding	Sewer Conveyance, Blockage and Sedimentation
19	Temperature	Groundwater Flooding	Buildings and Contents	Impact of External Flooding on Intra-urban Drainage Systems
20	Agricultural Impacts	Environmental Regulation	Urbanisation	Urbanisation
21	Environmental Regulation	River Vegetation and Conveyance	Rural Land Management	Rural Land Management
22	Groundwater Flooding	Stakeholder Behaviour	Stakeholder Behaviour	Stakeholder Behaviour

23	Science and Technology (known to be important but not quantified)

4.1. Climate Change: Precipitation

Climate change is the dominant driver of increased flood risk in the UK [20]. With regard to precipitation, multiple, unprecedented rainfall events during the last decade suggest that the impacts of this driver are increasing faster than was envisioned in the 2008 Foresight update. New rainfall records are being established with increasing regularity: e.g. Cumbria (Cockermouth) in November 2009 [6]; central, southern and southeast England in January 2014 [8], and; northern England, Northern Ireland and parts of Wales during winter 2015/16 [9]. There have also been multiple examples of severe, localised flooding caused by intense rainstorms, including the June 2012 'supercell' thunderstorms over Newcastle [7] and 2019 flooding in Lincolnshire and Kent during an 'exceptionally wet June' [10]. It is increasingly apparent that extreme rainfall events are not restricted to any one part of the UK. Extreme monthly rainfall, wherein two to three times the long-term average is recorded, has occurred across most parts of the country, and this is likely to continue (**Error! Reference source not found.**). As a direct consequence, exceptionally high, record-breaking river flows are being more frequently observed (Figure 2), e.g. in northern England during winter 2015-2016, which led to widespread fluvial flooding [9]. UK winter rainfall is expected to increase and, currently, there is a 34% probability of an unprecedented winter monthly rainfall total occurring in at least one month, in at least one region (south east England, Midlands, East Anglia and north east England) every year [21]. Heavier, short-duration summer rainfall events are also predicted to become more frequent and intense due to climate change, increasing the chance of exceeding the Meteorological Office/Environment Agency accumulation threshold (30 mm h^{-1}), which indicates that flash flooding is likely [22]. Rainfall was identified as a critical driver of urban flood risk in 2004 and 2008 and we conclude that it has strengthened during the last decade.

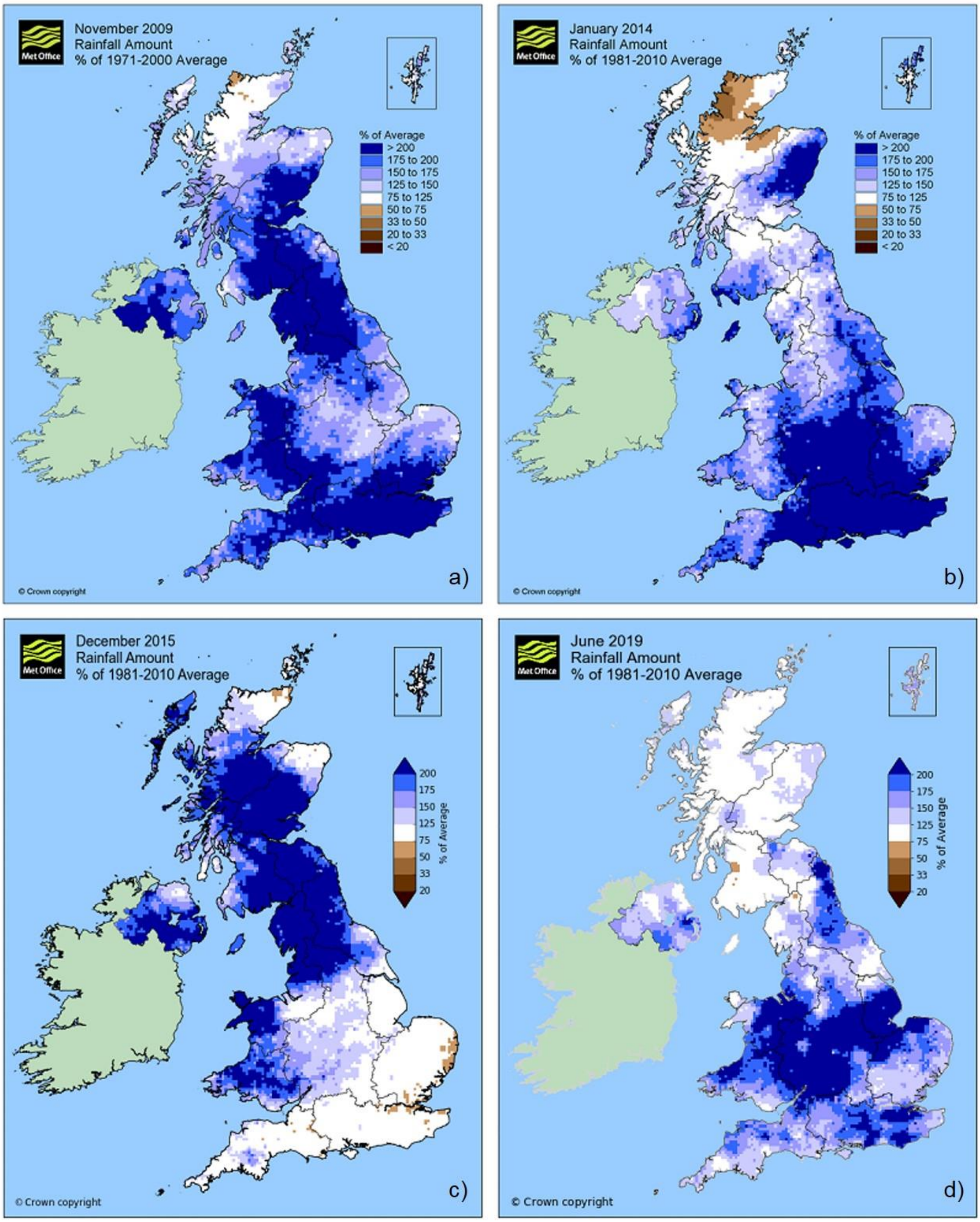

Figure 1 UK rainfall anomaly maps illustrating months that experienced two to three times the long-term average; a) November 2009, b) January 2014, c) December 2015, d) June 2019. Note that the long-term average in a) refers to the period 1971-2000, and in b-d) refers to the period 1981-2010. Source: Met Office, 2019.

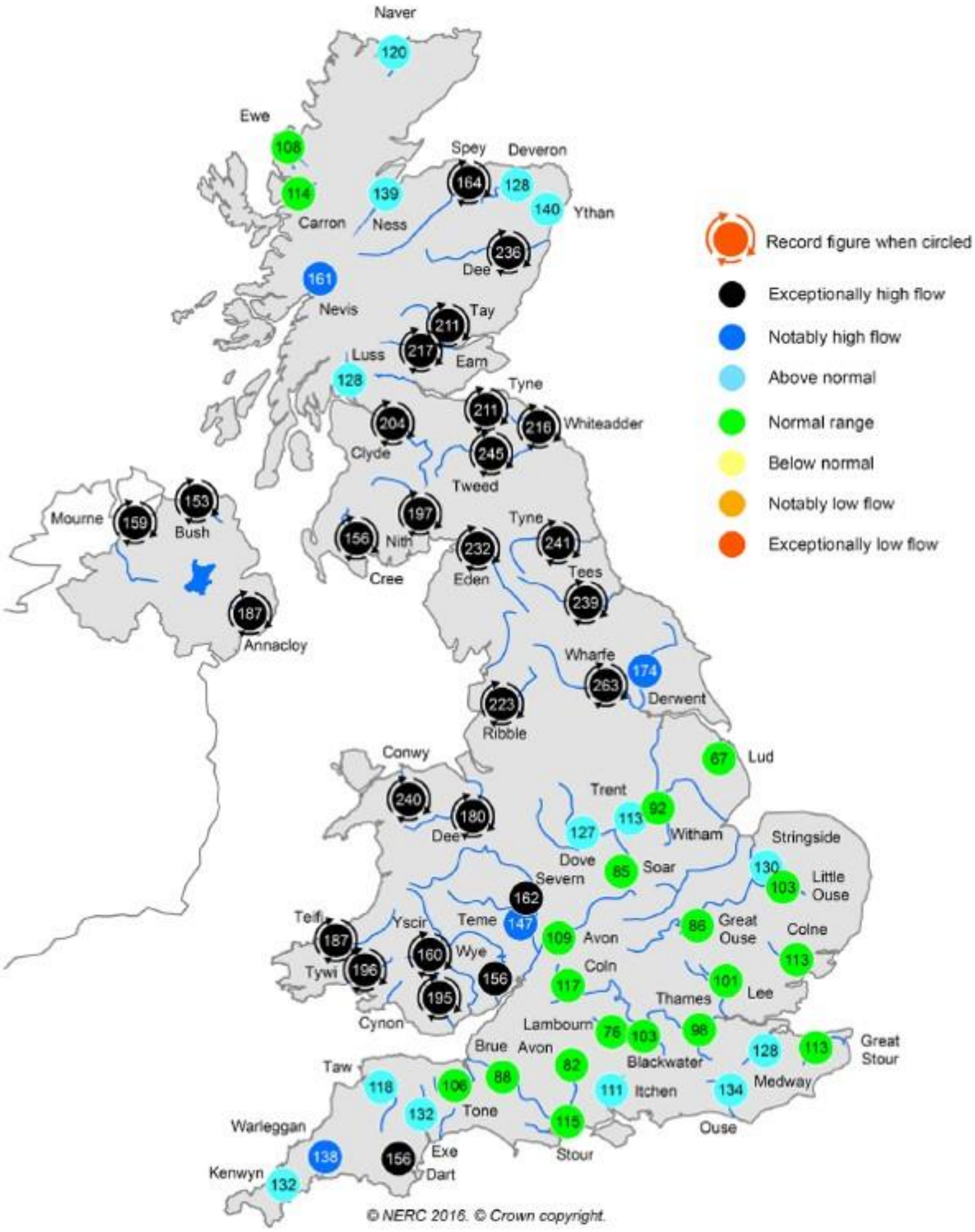

Figure 2 Mean river flows for November 2015 to January 2016 expressed as a percentage of long-term average flows. New flow records are circled with black arrows. Source: Marsh et al., (2016).

4.2. Climate Change: Temperature

In the UK, the 10 warmest years in a series dating from 1884 have all occurred since 2002 and the last decade (2009-2018) has been, on average, 0.3°C warmer than the 1982-2010 average [3]. UKCP18 projections indicate that the UK climate is expected to continue to warm throughout the rest of this century, with annual average temperature increasing by between 0.5 and 5.7°C above the 1981-2000 baseline, depending on the future emissions trajectory and taking into account model uncertainty [14]. Summer convective rainfall events are expected to intensify in future warmer, moister environments [22], elevating temperature-driven flood risks. Temperature increases are thus occurring more rapidly than previously expected, and we conclude that this driver of urban flood risk has strengthened.

4.3. Climate Change: Relative Sea-Level Rise

Rates of mean Sea-Level Rise, at approximately 1.4 mm/year from the start of the 20th century [3], have remained relatively constant and within the uncertainty band for this driver. Nonetheless, *relative* Sea-Level Rise could become a more significant future driver of flood risk in parts of the country subject to subsidence. For example, based on UKCP18 projections, sea-level in the Thames Estuary in 2100 could rise by between 29-70 cm (low emissions scenario) and by between 53-115 cm (high emissions scenario), increasing flood risk to London more than was envisaged in 2008 [14]. The seriousness of the situation is illustrated by the fact that 200km of coastal defences would be highly vulnerable to failure if relative sea-level rose by 0.5m (equivalent to the sea-level rise associated with a 4°C increase in global mean temperature) [20]. Nationally, however, there is insufficient evidence to conclude that relative Sea-Level Rise as a driver of urban flood risk has increased significantly in intensity since 2008.

4.4. Climate Change: Waves

There are post-2008 examples, such as during December 2014 and, more recently, Storm Callum (October 11-12, 2018), of situations where coastal flooding and its impacts have been exacerbated by strong winds causing large waves to batter exposed coastlines, especially in the south and west of the UK [3]. This driver may further strengthen in the future as storms intensify and relative sea-level rises to allow greater inshore propagation of waves and inundation due to the over-topping of coastal defences. However, evidence to date is insufficient to support changing the intensity of waves as a driver of urban flood risk at the national scale.

4.5. Climate Change: Storm Surges

The December 2013, East Coast storm surge resulted in the highest ever recorded tides in the Humber and Thames Estuaries, as well as matching sea surface elevations recorded during the 1953 event [8]. During this event, extensive flooding (including in urban areas, such as Boston, Lincolnshire) and coastal erosion (especially at Happisburgh, Norfolk), coupled with severe damage to property, flood defences and other key infrastructure demonstrated the potential for this driver to substantially increase future flood risks. However, while it is probable that climate-change induced increases in storminess will lead to increases in the magnitude and frequency of surges, this was fully considered in the 2008 re-assessment and uncertainty regarding the impact of this driver remains high [14]. Hence, we conclude that the 2013 surge event does not provide a sufficient basis for strengthening this driver.

4.6. Catchment Runoff: Urbanisation

Urbanisation can lead to increases in overland flow and the risks associated with surface water flooding (at the local scale), and river flooding (at the catchment-scale). However, the future impacts of urbanisation on flood risk can be mitigated with effective management [11]. There is extensive literature on strategies to reduce flood risk associated with urbanisation that use Sustainable Drainage Systems (SuDS) [23] and Blue-Green infrastructure (BGI) [24], as exemplified by current development of the Ebbsfleet Garden City [25]. However, implementation of innovative urban flood risk management approaches and infrastructure continues to be hampered by socio-political, biophysical and governance barriers [26] and, in particular, by failure (in England) to enact Schedule 3 of the 2010 Flood and Water Management Act, which would require surface water drainage for new developments to comply with mandatory National Standards for SuDS [27]. Hence, while post-2008 legislation suggests that this driver *should* weaken in future, this is countered by the demonstrable lack of widespread progress during the last decade. We therefore conclude that the intensity of this driver has not yet changed.

4.7. Catchment Runoff: Rural Land Management

This driver is on the path to decreasing, in that both the science and practice of 'slowing the flow' in rural areas, to reduce flood risk in downstream urban communities, have advanced significantly since 2008. Theory-based analyses, and practical experience gained through implementation of Natural Flood Management (NFM) and Working with Natural Processes (WwNP) demonstrate the potential of rural land management to reduce localised flooding [28]. For example, Runoff Attenuation Features (RAFs) including permeable timber barriers and large woody debris in riparian areas of the catchment, have been shown to reduce flood propagation in small rural catchments, such as Belford Burn, Northumberland [29]. Nonetheless, linkages between land management and flood risk are specific to their spatial (catchment) and temporal (flood event) contexts [30], making upscaling problematic, and there is general agreement that further development of the evidence base around NFM and WwNP is needed [31]. In practice, the relationship between future rural land management and flood risk depends on future agricultural policy, which varies widely between socio-economic scenarios. In a 'National Enterprise' future, agricultural intensification for food security would likely increase risks associated with both localised, muddy flooding and river flooding. In a 'Global Sustainability' future, payments to farmers for soil conservation and flood risk reduction could turn this driver into a highly effective *response*. Overall, we conclude that this driver has weakened since 2008, though Brexit puts a question mark over whether this trend will be sustained.

4.8. Groundwater Systems and Processes: Groundwater Flooding

Since 2008, new evidence of the threat posed by groundwater flooding has emerged. For example, in 2013/14, extensive groundwater flooding prolonged the duration of flooding by several months [8]. That said, controls on the spatio-temporal extent of groundwater flooding remain poorly understood and groundwater flooding is usually a component of coincident flooding, rather than being a source of flooding in itself [32]. Also, the total number of properties thought to be at risk from groundwater flooding in England is being challenged due to advances in flood risk estimations [33]. There is no doubt that future changes to rainfall patterns, intensity, and duration could increase the significance of groundwater as a flood risk driver in the most susceptible catchments (e.g. chalk basins in the southeast UK). Overall, while groundwater systems and processes will remain an influential driver of coincident flood risk, we do not yet see sufficient evidence to change its intensity.

4.9. Fluvial Systems and Processes: Environmental Regulation

This driver is on the path to decreasing owing to advancements in both the science and practice of managing rivers and fluvial flood risks, as set out in post-2008 legislation, including the Flood and Water Management Act [27] and National Flood and Coastal Erosion Risk Management Strategy for England [34]. Overall, NFM and WwNP are helping to align environmental management with flood risk management better than in 2008, albeit that (as noted in the earlier discussion of the Rural Land Management driver), further development of the evidence base around NFM and WwNP is needed [31]. In practice, the relationship between environmental regulation and flood risk depends on future river management policies, which vary widely between socio-economic scenarios, within which the functions of rivers, and the ecosystem services that they provide, are valued differently. Despite the issues that remain regarding the choice between hard defences or more natural management of the riverine environment, we conclude that this driver has weakened significantly since 2008.

4.10. Fluvial Systems and Processes: River Morphology and Sediment Supply

This driver is related to the Environmental Regulation driver, which is presumed to constrain the removal of sediment in response to adverse morphological change except where this can be justified as being the only practical management activity [11]. Agencies are now better at managing rivers in general, and river sediments in particular, supported by applicable research, including that into WwNP [28], and practical guidance, e.g. the Environment Agency's *Channel Management Handbook* [35] and HR Wallingford's *Green Approaches to River Engineering* [36]. We therefore conclude that advances in the science and practice of managing river morphology, sediment supply and consequential fluvial flood risks have led to the weakening of this driver.

4.11. Fluvial Systems and Processes: River Vegetation and Conveyance

The impacts of this driver on the probability of flooding are complex in both time and space, e.g. vegetation-related reduction in the conveyance capacity of an intra-urban channel is likely to increase flood risk, however, increased energy losses due to vegetation upstream of urban areas may reduce flood risk through the increased attenuation of flows on flood-suitable, natural floodplains [11]. This driver is interlinked with the other two drivers in the Fluvial Systems and Processes set through changes in how watercourses are currently managed. As noted above, agencies are now better at managing rivers in general, and vegetation and conveyance in particular, with less wholesale removal of vegetation (which also lowers maintenance budgets) and a greater focus on habitat and biodiversity [35]. Despite these advances, examples of best practice remain patchy and we do not yet see sufficient evidence to change the intensity of this driver.

4.12. Urban Systems and Processes: Urbanisation and Intra-urban Runoff

The area of impermeable surfaces in towns and cities has risen by 22% since 2001 [5] including an increase in residential hardstanding, e.g. patios, extensions, paved driveways. Conversely, there are many examples of effective management of flood risk from intra-urban runoff using BGI and SuDS, e.g. Llanelli [37] and Greener Grangetown [38]. Nonetheless, building on, and paving over, floodplains continues and (as mentioned in relation to Urbanisation) implementation of BGI and SuDS remains suboptimal. In practice, examples of best practice are geographically isolated and have yet to become part of mainstream urban development and retrofit. In the context of this driver, designing for exceedance is imperative to reduce the impacts that arise when flows exceed the capacity of the urban drainage system and should be encouraged to help manage intra-urban, pluvial flooding under climates featuring rainstorms that are both more intense and more frequent [39]. Over the next 50 years, increases in urban development may lead to a 60–220% increase in damages caused by intra-urban, surface water flooding [40], which suggests that this driver may become more prevalent in future, depending on the type and extent of urban development, and the scenario-related degree to which SuDS and BGI are implemented to mitigate rising urban flood risks. To date, however, there is little evidence that the intensity of this driver has changed significantly since 2008.

4.13. Urban Systems and Processes: Sewer Conveyance, Blockage and Sedimentation

Urban sewerage infrastructure systems have a finite design capacity to deal with extreme rainfall events, resulting in sewer surcharge when that capacity is exceeded, e.g. Newcastle 2012 ‘Toon Monsoon’ [41]. Additionally, surcharge may occur during lesser events if the sewer’s conveyance is reduced by blockage or sedimentation. Despite investment in sewer replacements and upgrades, issues such as misconnections and ‘fatbergs’ remain as problematic today as in 2008, with the additional issue of ‘wet wipes’ becoming another cause of blockages. This driver is also interlinked with the Intra-urban Asset Deterioration driver, as discussed below, e.g. driving the risk of internal flooding, which affected over 5000 properties during the period 2017–2018. Internal flooding is further exacerbated by severe weather events, demonstrating a key link between urban infrastructure and climate change drivers of flood risk [42]. In the 2008 study, the capacity of the sewerage system was rated as one of the most important drivers of future risk. We believe that this is still the case in 2019. There is, however, little evidence that the intensity of this driver has changed significantly.

4.14. Urban Systems and Processes: Impact of External Flooding on Intra-urban Drainage Systems

There is evidence that flooding from external sources causing loss of conveyance in piped and pumped drainage systems is happening more frequently, e.g. Carlisle (2005), Hull (2007), and Hebden Bridge (several times since 2015). Conversely, there are now fewer uncontrolled outfalls than in the past and an aspiration for zero uncontrolled discharges from sewers by 2050 [43]. Also, widespread implementation of NFM could reduce the intensity of this driver of urban flood risk. Given these conflicting trends, the intensity of this risk is unchanged from that in previous Flood Foresight studies.

4.15. Urban Systems and Processes: Intra-urban Asset Deterioration

Risk associated with ageing infrastructure is a global challenge, as assets reach the end of their useful service lives and require replacement or upgrading at significant cost [44]. For example, Thames Water's sewer pipes are, on average, 80 years old, with 34% over 100 years old. 67% of leaks occur under London, making it challenging, disruptive and costly to repair them [45]. Investment in sewer system expansion and treatment plant upgrades has taken priority over improving the current sewer system. Simply put, rehabilitation of intra-urban assets is not keeping pace with deterioration. Whaley Bridge (July 2019) is an example of flood risk exacerbated by the interaction between extreme rainfall and ageing water control infrastructure; increases in the water levels in Toddbrook Reservoir led to large volumes of water flowing down the spillway of the dam, damaging the protective concrete facing and putting the dam, located above the Derbyshire town of Whaley Bridge, at risk of collapse [46]. The number of dams and linear flood defences in the UK at similar risk is currently unknown. This driver was rightly regarded as a crucial driver of future urban flood risk in 2008, it has increased in intensity since 2008, and it is likely to intensify further in the future.

4.16. Coastal Processes: Coastal Morphology and Sediment Supply

The 2008 Flood Foresight update noted that risks related to morphological changes at the coast arose under all future scenarios, with a plausible risk of much greater impacts should global warming lead to an extreme, though unlikely, sea-level rise. In rural areas, managed retreat, coupled with realignment or abandonment of coastal defences, should mitigate the impacts of this driver, but problems with implementing this policy suggest that its impacts on flood and coastal erosion risks may strengthen, depending on the emphasis placed on supporting rural businesses and achieving national food security. The impact of this driver in urban areas will depend primarily on the economic feasibility of maintaining and, in due course raising/replacing/expanding the hard defences (sea walls, embankments and movable barriers) that protect towns and cities at risk from coastal flooding and erosion. Many of the UK's urban conurbations are situated on coasts or estuaries and these will be protected in all but the most extreme relative sea-level futures [47]. This may not be the case for smaller coastal towns, whose populations may have to relocate inland as part of managed retreat or 'coastal roll-back'. Overall, none of this has changed substantially in the last decade and so this driver is unchanged.

4.17. Human Behaviour: Stakeholder Behaviour

Stakeholders, including individuals, communities and institutions, impact urban flood risk at different scales, and with positive and negative effects. Much more information on flood risk is now available to stakeholders than was the case in 2008, including the Environment Agency's interactive maps of fluvial/coastal, surface water, and reservoir flooding (https://flood-warning-information.service.gov.uk/long-term-flood-risk/map). Intense media coverage of flooding continues due to the increased frequency of flooding in the UK and worldwide, and this has raised overall awareness of flood risks. Social media now makes it possible for people to share their experiences and concerns in near real-time before, during and after flood events [48]. Despite these and other examples of developments that *should* increase stakeholder flood awareness, resilience and preparedness, there is no evidence that this *has* actually reduced the misery and losses flooding causes. Many people still do not perceive that they have a flood risk, especially with respect to surface water and flash floods [49]. We conclude that the intensity of stakeholder behaviour as a driver of flood risk has not changed significantly.

4.18. Socio-economics: Buildings and Contents

Capital investment in buildings and their contents continues apace, which leads to greater losses when newer buildings of higher economic worth are inundated. Damage to higher value property and contents is acknowledged to be a more serious impact of flooding in the Environment Agency's National Assessment of Flood Risk [50], although the 'relative pain' of damages in terms of proportion of the household income may be reduced in wealthy households [20]. This driver is most effective where new buildings are situated on a river or coastal floodplain. The potential of this driver to increase flood losses is further amplified by recent increases in the degrees to which industry, commerce, public services and daily life are becoming dependent on supply chains and/or technologies that are vulnerable to wide scale disruption by flooding of key hubs, servers or infrastructure (an overlap with section 4.19 Infrastructure impacts). For example, the risks to internet infrastructure in the USA due to sea-level rise is expected to increase due to the vulnerability of buried fibre conduit and co-location centres in coastal areas, with ~6,600 km of fibre conduit potentially under water and over 1100 co-location centres potentially surrounded by water by 2023 [51]. Climate-related risks to Information and Communications Technology (ICT) networks are summarised in the 2017 Climate Change Risk Assessment [52], but more research is needed to fully explore the impact of future flood risk on technologies that are vulnerable to widespread disruption during flood events. We therefore suggest that this receptor driver has increased in intensity since 2008.

4.19. Socio-economics: Urban Impacts

There are signs of positive change for the future with greater flood resilience being built into new homes, communities and towns, e.g. the Ebbsfleet Garden City, where integrated design of BGI networks reduce flood risk and increase climate resilience [25]. However, to reduce this driver at a national scale, major changes are needed in the urban fabric. Such changes probably cannot be achieved without revisions to planning regulations and building codes, a greater commitment to flood-proofing of buildings in floodplains, and changes to flood insurance that encourage rebuilding for resilience, rather than 'as was'. Unfortunately, despite examples of best practice, there is little evidence to suggest any reduction in the intensity of urban impacts as a driver of future flood risk nationally.

4.20. Socio-economics: Infrastructure Impacts

Increased frequency of flooding from all sources has been identified as the most significant climate change risk to UK infrastructure (including transport, energy, water, waste and digital communications) [52]. The impacts of flooding on infrastructure are now better understood, as set out in the 2017 Climate Change Risk Assessment [20, 52] and the first National Infrastructure Assessment in 2018 [53], and they are higher up the political agenda. The National Infrastructure Commission (NIC) highlights the increasing pressure that UK infrastructure is under due to climate change, a growing population and higher environmental standards, exacerbated by ageing infrastructure. By the 2080s, the number of infrastructure assets exposed to flooding more frequently than 1:75 years on average is expected to increase by 30% (under a 2°C climate change projection) and by 200% under a 4°C projection, and the length of railway lines exposed to flooding is expected to increase by 53% and 160% (under 2°C and 4°C climate change projections, respectively, for flooding more frequent than 1:75 years on average) [20]. Another example is flying; overall UK aviation activity grew by 17.8% between 2006 and 2016 [54]. There are several recent examples of how flooding has impacted aviation infrastructure and passengers, including Christmas Eve 2013 and the heavy rainfall that led to flooding and the outage of the three airport-operated electrical substations at Gatwick Airport, leading to flight cancellations that impacted more than 13,000 passengers [55]. However, recommendations made to date, by the NIC and others, have not yet been acted on. This suggests that this driver may strengthen in future unless timely action is taken to overcome long-standing constraints associated with low public awareness and a focus on short-term value [53]. As with the other receptor drivers, some cities, towns and communities are taking steps to make their infrastructure flood resilient, but this trend is far from ubiquitous. Hence, the intensity of this driver is unchanged.

4.21. Socio-economics: Agricultural Impacts

The impacts of flooding on farming are highly scenario-dependent. Uncertainty is amplified by Brexit and lack of knowledge concerning what will follow the Common Agricultural Policy. In any case, in the context of urban flood risk, the impacts of agricultural losses are indirect. It follows that, at present, there no basis on which to gauge the impacts of possible changes in the intensity of agricultural impacts as a driver of future urban flood risk.

4.22. Socio-economics: Social Impacts

This driver has strengthened over the last decade and flood disadvantage (the combination of exposure to flooding and social vulnerability) is becoming increasingly, geographically concentrated. 50% of the most socially vulnerable people that live in flood prone urban areas are situated in ten Local Authorities (Hull, Boston, Belfast, Birmingham, East Lindsey, Glasgow, Leicester, North East Lincolnshire, Swale District, and Tower Hamlets) [56]. 249 of the UK's most flood disadvantaged neighbourhoods were identified using the Joseph Rowntree Foundation's 'climate just analysis' in a study of whether current approaches to flood investment are taking sufficient account of social vulnerability, or wider deprivation [57]. Of the 1,493 flood alleviation schemes in the investment pipeline, only 100 were located in flood disadvantaged neighbourhoods, demonstrating the uneven distribution of flooding impacts based on enhanced exposure, sensitivity and adaptive capacity [57]. Attitudes are hardening around the social impacts of flooding and the responsibility flood victims bear for 'choosing' to live on a floodplain. This is leading to increasing tensions between social groups, marginalisation of those at risk and reduced social cohesion, all of which further increases the impacts of flooding on mental health, [58]. This receptor driver is therefore found to have increased in intensity since 2008.

4.23. Socio-economics: Science and Technology

This driver was assessed as important but not quantified in the 2004 and 2008 studies. We concur with earlier conclusions that this driver operates through other drivers, such as: Buildings and Contents (e.g. computer servers in basements); Infrastructure Impacts (the information technology networks); and Urban Impacts (real-time forecasting of the locations of floods and their impacts). We recognise that this driver is important and highly complex, but we see no more compelling case for it to be scored and ranked than existed previously. That said, recent advances in science and technology have led to marked improvements in UK weather forecasting and flood warning systems, supporting increased levels of preparedness, and allowing more effective event management and faster recovery. If these trends continue then this driver may weaken, and it could potentially become an effective response to rising urban flood risks in the future.

4.24. New driver: Urban Systems and Processes: Loss of Floodable Urban Spaces

This driver refers to the loss of urban spaces that previously contributed to reducing flood risk through infiltration, conveyance, storage and/or attenuation. This includes; the loss of urban green areas and brownfield land to buildings and infrastructure; changes in the types or management regimes of urban green spaces that affect their capacity to absorb rainfall and accept intra-urban surface water or floodwater entering the urban area from a peri-urban waterbody, and; changes in exceedance pathways designed to manage flows that surcharge the urban drainage system. In short, this driver represents reductions in urban spaces that are ‘flood suitable’, albeit that these are spaces where inundation is temporary. In many UK cities, ‘green belts’ limit urban expansion, focusing development through ‘infilling’ and redevelopment of brownfield sites, giving it strong potential to increase future urban flood risks. However, expanded implementation of SuDS and BGI would turn this driver into an effective response, particularly where green spaces are conserved and their functionality in delivering not only flood risk benefits, but also a range of other social and environmental co-benefits, is optimised. For example, integrating green spaces and grey infrastructure to create stormwater treatment trains is known to deliver multiple co-benefits [23].

4.25. New driver: Socio-economics: Indirect Economic Impacts

This driver encompasses the indirect financial and economic impacts of flood events, including losses from capital and labour productivity disruptions, e.g. when flooded roads interrupt commuting with consequential disruption to economic activities outside the inundated area. Traditional assessment of economic losses from floods consider only direct damages to buildings, contents and infrastructure. However, a large proportion of the total economic burden of floods may be attributed to indirect, knock-on effects on goods, services, supply chains and productivity, during both the flood and its aftermath, until the economy fully recovers. Often, the economic sectors most adversely affected are not those that are directly impacted, as was observed in the case of the 2007 summer floods in Yorkshire and Humberside, where indirect damages accounted for over half of the total ‘flood footprint’ [59]. If fully recognised and quantified, this driver would have the potential to rival Infrastructure Impacts as the strongest driver of future economic flood risk.

Table 3 Overarching changes to the intensity of the 2008 Flood Foresight drivers of combined fluvial/coastal and intra-urban flood risk. Note that the drivers are not ranked.

Intensity	Driver
Strengthened	Precipitation
	Temperature
	Intra-urban Asset Deterioration
	Buildings and Contents
	Social Impacts
Remained within the uncertainty bands allocated to them in 2008	Relative Sea-Level Rise
	Waves
	Surges
	Urbanisation
	Groundwater Flooding
	River Vegetation and Conveyance
	Urbanisation and Intra-urban Runoff
	Sewer Conveyance, Blockage and Sedimentation
	Impact of External Flooding on Intra-urban Drainage System
	Coastal Morphology and Sediment Supply
	Stakeholder Behaviour
	Urban Impacts
	Infrastructure Impacts
	Agricultural Impacts
Weakened	River Morphology and Sediment Supply
	Rural Land Management
	Environmental Regulation
Science and Technology (not quantified or ranked in the 2008 study)	

5. Discussion and Conclusion

Local and national flood risks have increased since 2008 and are expected to increase further in future owing to climate change, urbanisation, reductions in urban green spaces and deteriorating urban water management infrastructure [5, 14, 44]. In their 2018 Preliminary Flood Risk Assessment, the Environment Agency identify four periods of flooding (fluvial and coastal flooding in 2012, winter 2013/2014, winter 2015/2016 and early-2017) that have had significant, harmful consequences at the national level for public health, the economy, the environment and cultural heritage, and have also significantly changed how UK flood risk is understood and managed [4]. This, and other empirical evidence, together with advances in scientific knowledge, techniques and practice over the last decade has informed our qualitative reassessment and updating of the drivers of future UK fluvial/coastal and intra-urban flood risks.

The intensity of most of the drivers remains within the uncertainty bands identified in the Flood Foresight reports [10, 11] (**Error! Reference source not found.**). However, we perceive significant strengthening in five drivers (Precipitation, Temperature, Intra-urban Asset Deterioration, Buildings and Contents, and Social Impacts) and weakening in three (River Morphology and Sediment Supply, Rural Land Management, and Environmental Regulation). Further, we propose two new drivers: Loss of Floodable Urban Spaces, and Indirect Economic Impacts, which we suggest may significantly impact future urban flood risk.

Climate change continues to amplify the source drivers. Rainfall, in particular, is a major driver of urban flood risk that has strengthened in intensity since 2008. Relative Sea-Level Rise and increased storminess, coupled with increased precipitation and rising groundwater (leading to coincident flooding) are critical drivers of flood risk in coastal cities. Precipitation-driven flood risk is further influenced by catchment geography and geology, antecedent conditions, long-term weather patterns, rural land use, socio-economic change, and urban planning, including conventional urbanisation versus implementation of Blue-Green Cities [11]. These drivers do not influence the flooding system in isolation; changes in flood risk result from their interactions.

The limited capacities of sewerage systems remains a significant driver of future urban flood risk, and one that is expected to increase. Intra-urban asset deterioration, and the associated risks from ageing infrastructure, are a global challenge as assets reach the end of their design lives. Replacement of assets in urban areas is challenging, disruptive and extremely costly, and the rehabilitation is not keeping pace with deterioration. Widespread implementation of SuDS and BGI helps reduce pressure on combined sewers and can lengthen their useful lives. However, SuDS and BGI cannot replace piped urban drainage systems or negate this driver of future flood risk. Increased investment in improving existing sewer systems, and maintenance to reduce the fragility of dams and linear flood defences, is essential.

Two socio-economic, receptor drivers of flood risk have also strengthened during the last decade; Social Impacts (risk to life and health, and the intangible impacts of flooding on communities) and Buildings and Contents (due to continued capital investment that leads to greater losses when newer buildings of higher economic worth are inundated). This demonstrates the growing importance of the social and economic choices made by communities and their elected representatives in helping manage future flood risk.

The 2008 Flood Foresight study found that better science and understanding of driver impacts had led to upwards reappraisal of the risks posed by flooding from fluvial sources [11]. In contrast, we find that Environmental Regulation, and River Morphology and Sediment Supply (both in the Fluvial Systems and Processes driver set), have weakened as drivers, owing to advancements in both the science and practice of managing rivers and fluvial flood risks, improved guidance and legislation [34, 35], and development of approaches such as NFM and WwNP that are helping to align environmental management with flood risk management. Similar advances in the science and practice of 'slowing the flow' in rural areas to reduce flood risk in downstream urban communities have led to a weakening of the Rural Land Management driver. However, there is no certainty that these weakening trends will continue, as the relationship between rural land management, river management and future flood risk depends on agricultural and river management policies, which are certain to be revised post-Brexit.

Clearly, the path chosen by the UK post-Brexit will manifestly affect future urban flood risk. Updating the socio-economic and climate change scenarios, and using the outcomes to derive new scenario-based driver rankings (e.g. Table 2), was beyond the scope of this review. However, we strongly recommend that the drivers of future flood risk be fully re-assessed in 2020 to account for the significant changes that have occurred since 2008, to consider the UKCP18 climate change projections [14], and to evaluate potential near-term changes in flood risk management, social, economic, agricultural, planning and environmental policies.

Acknowledgements. We thank Professor Richard Ashley for his generous advice and helpful discussion concerning past, current and future drivers of urban flood risk. This research was performed as part of an interdisciplinary project undertaken by the EPSRC Urban Flood Resilience Research consortium under grant number EP/P004180/1 (www.urbanfloodresilience.ac.uk).

Competing interests. We declare that we have no competing interests.

Authors' contributions. E.C.O. and C.R.T. conceived the study and drafted the manuscript.

Funding. This work was supported by the Engineering and Physical Sciences Research Council [grant number EP/P004180/1].

References

[1] UN. 2018 World urbanisation prospects: The 2018 revision [key facts]. https://esa.un.org/unpd/wup/Publications/Files/WUP2018-KeyFacts.pdf accessed 18.03.19.

[2] Committee on Climate Change. 2017 UK Climate Change Risk Assessment 2017. Synthesis report: priorities for the next five years. Committee on Climate Change. https://www.theccc.org.uk/wp-content/uploads/2016/07/UK-CCRA-2017-Synthesis-Report-Committee-on-Climate-Change.pdf accessed 23.10.19.

[3] Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A. & Legg, T. 2019 State of the UK climate 2019. *International Journal of Climatology* **39**, 1-55. (DOI:10.1002/joc.6213).

[4] Environment Agency. 2018 Preliminary Flood Risk Assessment for England. Environment Agency, Bristol, UK. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/764784/English_PFRA_December_2018.pdf accessed 16.08.19.

[5] Committee on Climate Change. 2019 Progress in preparing for climate change. Committee on Climate Change 2019 Report to Parliament.

[6] Sibley, A. 2010 Analysis of extreme rainfall and flooding in Cumbria 18-20 November 2009. *Weather* **65**, 287-292. (DOI:10.1002/wea.672).

[7] Parry, S., Marsh, T. & Kendon, M. 2013 2012: from drought to floods in England and Wales. *Weather* **68**, 268-274. (DOI: 10.1002/wea.2152).

[8] Thorne, C. 2014 Geographies of UK flooding in 2013/4. *The Geographical Journal* **180**, 297-309. (DOI:10.1111/geoj.12122).

[9] Marsh, T., Kirby, C., Muchan, K., Barker, L., Henderson, E. & Hannaford, J. 2016 The winter floods of 2015/2016 in the UK - a review. Centre for Ecology & Hydrology, Wallingford, UK.

[10] CEH. 2019 UK Hydrological Status Update - July 2019. Centre for Ecology & Hydrology (CEH). https://www.ceh.ac.uk/news-and-media/blogs/uk-hydrological-status-update-july-2019 accessed 20.08.19.

[11] Evans, E. P., Simm, J. D., Thorne, C. R., Arnell, N. W., Ashley, R. M., Hess, T. M., Lane, S. N., Morris, J., Nicholls, R. J., Penning-Rowsell, E. C., et al. 2008 *An update of the Foresight Future Flooding 2004 qualitative risk analysis*. Cabinet Office, London.

[12] Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Sayers, P., Thorne, C. & Watkinson, A. 2004 Foresight Future Flooding, Volume I and Volume II. Office of Science and Technology, London.

[13] Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., et al. 2007 Global climate projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds). Cambridge University Press, Cambridge.

[14] Lowe, J., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., Edwards, T., Fosser, G., et al. 2018 *UKCP18 Science Overview report*. Met Office Hadley Centre, Exeter (2018).

[15] Bye, P. & Horner, M. 1998 Easter floods 1998: report by the Independent Review Team to the Board of the Environment Agency. Environment Agency, Bristol, UK.

[16] IPCC. 2000 Special Report on Emissions Scenarios (SRES): A Special Report of Working Group III of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press: Cambridge, UK.

[17] Penning-Rowsell, E. C. 2015 A realistic assessment of fluvial and coastal flood risk in England and Wales. *Transactions of the Institute of British Geographers* **40**, 44-61. (DOI:10.1111/tran.12053).

[18] Pitt, M. 2008 *The Pitt Review: Learning Lessons from the 2007 Floods. Cabinet Office*.

[19] Defra. 2005 *Making Space for Water: Taking Forward a New Government Strategy for Flood and Coastal Erosion Risk Management in England*. Delivery Plan. London: Department for Environment, Food and Rural Affairs).

[20] Sayers, P., Horritt, M., Penning-Rowsell, E. & Mckenzie, A. 2015 *Climate Change Risk Assessment 2017: Projections of future flood risk in the UK*. Research undertaken by Sayers and Partners on behalf of the Committee on Climate Change. Published by Committee on Climate Change, London.

[21] Thompson, V., Dunstone, N. J., Scaife, A. A., Smith, D. M., Slingo, J. M., Brown, S. & Belcher, S. E. 2017 High risk of unprecedented UK rainfall in the current climate. *Nature Communications* **8**, 107. (DOI:10.1038/s41467-017-00275-3).

[22] Kendon, E. J., Roberts, N. M., Fowler, H. J., Roberts, M. J., Chan, S. C. & Senior, C. A. 2014 Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change* **4**, 570. (DOI:10.1038/nclimate2258).

[23] Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R. & Kellagher, R. 2015 CIRIA report C753 The SuDS Manual. CIRIA, London.

[24] Lawson, E., Thorne, C., Ahilan, S., Allen, D., Arthur, S., Everett, G., Fenner, R., Glenis, V., Guan, D., Hoang, L., et al. 2014 Delivering and evaluating the multiple flood risk benefits in Blue-Green Cities: an interdisciplinary approach. In *Flood Recovery, Innovation and Response IV* (eds. D. Proverbs & C. A. Brebbia), pp. 113-124, WIT Press.

[25] Ebbsfleet Development Corporation. 2017 Ebbsfleet Implementation Framework. https://ebbsfleetdc.org.uk/wp-content/uploads/2017/04/Ebbsfleet-Implementation-Framework.pdf accessed 23.08.19.

[26] O'Donnell, E., Lamond, J. & Thorne, C. 2017 Recognising barriers to implementation of Blue-Green infrastructure: a Newcastle case study. *Urban Water Journal* **14**, 964-971. (DOI:10.1080/1573062X.2017.1279190).

[27] FWMA. 2010 F*lood and Water Management Act, 2010*. Elizabeth II. Chapter 29. Her Majesty's Stationery Office, London, UK.

[28] Burgess-Gamble, L., Ngai, R., Wilkinson, M., Nisbet, T., Pontee, N., Harvey, R., Kipling, K., Addy, S., Rose, S., Maslen, S., et al. 2017 *Working with Natural Processes–Evidence Directory*. Environmental Agency, Report No. SC150005. Environment Agency, *Bristol, UK.*

[29] Nicholson, A., Wilkinson, M., O'Donnell, G. & Quinn, P. 2012 Runoff attenuation features: a sustainable flood mitigation strategy in the Belford catchment, UK. *Area* **44**, 463-469. (DOI:10.1111/j.1475-4762.2012.01099.x).

[30] Pattison, I. & Lane, S. N. 2012 The link between land-use management and fluvial flood risk: A chaotic conception? *Progress in Physical Geography: Earth and Environment* **36**, 72-92. (DOI:10.1177/0309133311425398).

[31] Dadson, S. J., Hall, J. W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., Heathwaite, L., Holden, J., Holman, I. P. & Lane, S. N. 2017 A restatement of the natural science evidence concerning catchment-based 'natural'flood management in the UK. *Proc. R. Soc. A* **473**. (DOI:10.1098/rspa.2016.0706).

[32] Ascott, M. J., Marchant, B. P., Macdonald, D., McKenzie, A. A. & Bloomfield, J. P. 2017 Improved understanding of spatio-temporal controls on regional scale groundwater flooding using hydrograph analysis and impulse response functions. *Hydrological Processes* **31**, 4586-4599. (DOI:10.1002/hyp.11380).

[33] McKenzie, A. & Ward, R. 2015 Estimating numbers of properties susceptible to groundwater flooding in England. British Geological Survey Open Report, OR/15/016. 16pp.

[34] Environment Agency. 2011 *Understanding the Risks, Empowering Communities, Building Resilience.* National Flood and Coastal Erosion Risk Management Strategy for England. Environment Agency, Bristol, UK.

[35] Williamson, P., Ogunyoye, F., Dennis, I., Douglas, J., Hardwick, M., Sayers, P., Fisher, K., Thorne, C. & Holmes, N. 2015 *Channel Management Handbook: Working with Natural Processes*. Environment Agency, Bristol, UK. Environment Agency, Bristol.

[36] Roca, M., Escarameia, M., Gimeno, O., de Vilder, L., Simm, J., Horton, B. & Thorne, C. 2017 *Green approaches in river engineering-supporting implementation of Green Infrastructure*. HR Wallingford, Wallingford, UK.

[37] Ellis, C., Cripps, R., Russ, M. & Broom, S. 2016 Transforming water management in Llanelli, UK. *Proceedings of the Institution of Civil Engineers-Civil Engineering* **169**, 25-33. (DOI:10.1680/jcien.15.00027).

[38] Greener Grangetown. 2018 Greener Grangetown project completion marked by Welsh Environment Minister. https://greenergrangetown.wordpress.com/2018/10/10/greener-grangetown-project-completion-marked-by-welsh-environment-minister-gweinidog-amgylchedd-cymru-yn-nodi-cwblhau-project-grangetown-werddach/ accessed 23.08.19.

[39] Digman, C., Ashley, R., Hargreaves, P. & Gill, E. 2014 *Managing Urban Flooding from Heavy Rainfall–Encouraging the Uptake of Designing for Exceedance–Recommendations and Summary*. CIRIA, C738a. CIRIA, London.

[40] Adaptation Sub-Committee. 2012 Climate change – is the UK preparing for flooding and water scarcity? Adaptation Sub-Committee of the Committee on Climate Change, Progress Report 2012. London, UK.

[41] Newcastle City Council. 2013 Summer 2012 Flooding in Newcastle upon Tyne. https://www.nwl.co.uk/_assets/documents/Summer_2012_Flooding_Report_-_final_-_July_2013.pdf accessed 04.10.19.

[42] Ofwat. 2019 Service and delivery report. January 2019. https://www.ofwat.gov.uk/wp-content/uploads/2019/01/Service-Delivery-Report-201718-25012019-Final.pdf accessed 28.08.19.

[43] UKWIR. 2019 How do we achieve zero uncontrolled discharges from sewers by 2050? UK Water Industry Research (UKWIR). https://ukwir.org/How-do-we-achieve-zero-uncontrolled-discharges-from-sewers-by-2050 accesssed 29.08.19.

[44] Speight, V. L. 2015 Innovation in the water industry: barriers and opportunities for US and UK utilities. *Wiley Interdisciplinary Reviews: Water*. (DOI:10.1002/wat2.1082).

[45] Thames Water. 2018 PR19 - Appendix 4 - Resilience - September 2018. https://corporate.thameswater.co.uk/-/media/Site-Content/Thames-Water/Corporate/AboutUs/Our-strategies-and-plans/PR19/Appendix-4-Resilience.pdf accessed 21.08.19.

[46] Heidarzadeh, M. 2019 Whaley Bridge dam collapse is a wake-up call: concrete infrastructure will not last forever without care. The Conversation, 5th August 2019. https://theconversation.com/whaley-bridge-dam-collapse-is-a-wake-up-call-concrete-infrastructure-will-not-last-forever-without-care-121423 accessed 16.08.19.

[47] Environment Agency. 2012 Thames Estuary 2100 (TE2100 Plan). London, UK.

[48] Bird, D., Ling, M. & Haynes, K. 2012 Flooding Facebook-the use of social media during the Queensland and Victorian floods. *Australian Journal of Emergency Management* **27**, 27-33.

[49] Cologna, V., Bark, R. H. & Paavola, J. 2017 Flood risk perceptions and the UK media: Moving beyond “once in a lifetime” to “Be Prepared” reporting. *Climate Risk Management* **17**, 1-10. (DOI:10.1016/j.crm.2017.04.005).

[50] Environment Agency. 2009 Flooding in England: A National Assessment of Flood Risk. Environment Agency, Bristol.

[51] Durairajan, R., Barford, C. & Barford, P. 2018 *Lights out: Climate change risk to internet infrastructure*. In Proceedings of the Applied Networking Research Workshop 2018, in Montreal, Canada, July 16, pp. 9-15. (DOI:10.1145/3232755.3232775).

[52] Dawson, R., Thompson, D., Johns, D., Gosling, S., Chapman, L., Darch, G., Watson, G., Powrie, W., Bell, S., Paulson, K., et al. *2016 UK Climate Change Risk Assessment Evidence Report: Chapter 4, Infrastructure*. Report *prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London*.

[53] National Infrastructure Commission. 2018 National Infrastructure Assessment. https://www.nic.org.uk/wp-content/uploads/CCS001_CCS0618917350-001_NIC-NIA_Accessible.pdf#page=85 accessed 27/08/19.

[54] Rouncivell, A., Timmis, A. J. & Ison, S. G. 2018 Willingness to pay for preferred seat selection on UK domestic flights. *Journal of Air Transport Management* **70**, 57-61.(DOI:10.1016/j.jairtraman.2018.04.018).

[55] McMillan, D. 2014 Disruption at Gatwick Airport Christmas Eve 2013. Independent Report to the Board of Gatwick Airport Ltd. https://www.gatwickairport.com/globalassets/publicationfiles/business_and_community/all_public_publications/2014/mcmillan_report_feb14.pdf accessed 22.10.19.

[56] Sayers, P., Penning-Rowsell, E. C. & Horritt, M. 2018 Flood vulnerability, risk, and social disadvantage: current and future patterns in the UK. *Regional environmental change* **18**, 339-352. (DOI:10.1007/s10113-017-1252-z).

[57] England, K. & Knox, K. 2015 Targeting flood investment and policy to minimise flood disadvantage. The Joseph Rowntree Foundation, June 2015. https://www.jrf.org.uk/report/targeting-flood-investment-and-policy-minimise-flood-disadvantage accessed 22.10.19.

[58] Greene, G., Paranjothy, S. & Palmer, S. R. 2015 Resilience and vulnerability to the psychological harm from flooding: The role of social cohesion. *American Journal of Public Health* **105**, 1792-1795. (DOI:10.2105/AJPH.2015.302709).

[59] Mendoza-Tinoco, D., Guan, D., Zeng, Z., Xia, Y. & Serrano, A. 2017 Flood footprint of the 2007 floods in the UK: The case of the Yorkshire and The Humber Region. *Journal of Cleaner Production* **168**, 655-667. (DOI:10.1016/j.jclepro.2017.09.016).