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The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom

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ABSTRACT

Study region: United Kingdom (UK).

Study focus: Climate change and urbanization pose significant threats for flooding and water quality in urban areas. This paper reviews the evidence concerning the combined impacts of urbanisation and climate on the urban water environment of inland catchments of the United Kingdom and assesses the degree of confidence in reported directions of change and response. It also assesses the utility of the evidence for setting environmental legislation and managing the urban water environment in the future and identifies knowledge gaps that limit effective and management interventions.

New hydrological insights: There is a lack of nationally research focused on the dual impacts of climate change and urbanisation on flooding and water quality in UK urban areas. This is despite there being a clear acceptance that flood risk is increasing, water quality is generally not meeting desirable levels, and that combined population and climate change projections pose a pressing challenge. The available evidence has been found to be of medium-high confidence that both pressures will result in (i) an increase in pluvial and fluvial flood risk, and (ii) further reduction in water quality caused by point source pollution and altered flow regimes. Evidence concerning urban groundwater flooding, diffuse pollution and water temperature was found to be more sparse and was ascribed a low-medium confidence that both pressures will further exacerbate existing issues. The confidence ascribed to evidence was also found to reflect the utility of current science for setting policy and urban planning. Recurring factors that limit the utility of evidence for managing the urban environment includes: (i) climate change projection uncertainty and suitability, (ii) lack of sub-daily projections for storm rainfall, (iii) the complexity of managing and modelling the urban environment, and (iv) lack of probable national-scale future urban land-use projections. Suitable climate products are increasingly being developed and their application in applied urban research is critical in the wake of a series of extreme flooding events across the UK and timely for providing state-of-the-art evidence on which to base possible future water quality legislation in a post Brexit-WFD era.

1. Introduction

The United Kingdom has a significant legacy of urban development and associated deterioration of the urban water environment

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which only began to improve with technology and environmentally focused legislation in the latter 20th C (Johnstone and Joran, 1996). Poor urban water quality continues to be a concern, especially with increasing population growth, the growing presence of new and un-controlled substances (Vörösmarty et al., 2010), a greater value attributed to ecosystem services (Green et al., 2015), and uncertainty over the impacts of climate change on controlling factors of water quality such as temperature and environmental flows (Acreman and Ferguson, 2010; Arnell et al., 2015).

Flooding of urban areas poses one of the greatest challenges to human safety and sustained economic growth within the UK with estimated expected annual damages from flooding of £1bn (Hall et al., 2005) and costs from recent flooding during the winter of 2015–2016 in excess of £5bn (KPMG, 2016). Changes to the timing and magnitude (depth) of rainfall events as a result of climate change are predicted to significantly alter the flooding experienced in many urban areas of the world including the UK and without suitable mitigation lead to increased future flood risk and associated damages (Ashley et al., 2005; Wheater and Evans, 2009). Recent widespread flooding across the UK during the winter storms of 2013/14 (Muchan et al., 2015) and 2015/16 (Priestley, 2016) have highlighted the significant impacts that flooding can have.

A number of studies and reviews have approached the topic of climate change and urban water environment impacts at the global scale (e.g. Praskievicz and Chang, 2009; Hunt and Watkiss, 2011; Kundzewicz et al., 2013), highlighting the challenges posed by a combination of climate change and rapid urban development. Additionally, a number of UK focused reviews exist assessing climate impacts upon the water environment in general (e.g. Watts et al., 2015; Arnell et al., 2015; Whitehead et al., 2013; Wilby, 2008; UK Met Office, 2011). What is lacking and currently required − given the need to appraise the existing evidence in light of potential changes to environmental legislation as a result of the UK leaving the European Union (Brexit) − is a review of the evidence concerning the urban environment in the UK. The aim of this paper is to assess the evidence concerning the current and future combined impacts of urbanisation and climate change on the urban water environment of inland catchments in the United Kingdom and the degree of confidence in reported directions of change and response. The coastal urban environment is subject to a wider range of climate and urbanisation related issues, and being well reviewed elsewhere (Hall et al., 2006) is not considered in this review. The paper first provides an overview of the pressures of urbanisation and climate change in the UK. It then undertakes an assessment of UK focused literature on both urban flooding and urban water quality, looking at current and future pressures. It additionally assesses confidence in the relevance and quantity of evidence reported for changes to the water environment. This assessment is used to assess the utility of the existing evidence for managing the urban water environment in the future. Conclusions are drawn concerning the current evidence and knowledge gaps are identified.

2. Urbanisation, urban water management, and climate change in the UK

Over 80% of the population in Britain live in urban areas and the population of the UK has risen from 32 million in 1901–64.6 million in 2014 (ONS, 2014). Significantly, the United Kingdom is one of ten countries with over 5% (5.7%) of total land area occupied by cities (Angel et al., 2011) and is set to undergo a period of extensive population growth to 74.3 million (15%) by 2039 (ONS, 2014) and extrapolated to 97.2 million (+53%) by the 2080 s (Sayers et al., 2015). This requires more than just expansion and intensification of existing urban areas, and the UK government is currently planning a number of new 'garden' towns and villages.

Flood management in the UK is based on the concept of risk analysis, with the likelihood of flooding assessed using an annual exceedance probability (AEP) such as the 1% AEP (1 in 100 year event) and consequence assessed according to hazard and the magnitude of consequences. The Department for Environment Food and Rural Affairs (Defra) has government oversight for policy, while the Environment Agency (EA − England and Wales) and Scottish Environment Protection Agency (SEPA − Scotland) are the implementing authorities charged with making detailed assessments and management of national and regional flood risk. Additionally private water companies, local councils, highway authorities and internal drainage boards have responsibilities for sewer systems, storm drainage, main roads, and low lying farmland respectively (Bubeck et al., 2013). 2.4 million properties are at risk of flooding from rivers and the sea, with the majority in urban areas (Environment Agency, 2009) whilst pluvial flooding is the largest cause of property flooding in UK, with an estimated 3.8 million properties at risk (Environment Agency, 2009), accounting for around 40% of flood damage (Defra, 2014). Estimates for groundwater flooding in the United Kingdom are variable, with figures indicating properties at risk ranging from 122,000 and 290,000 (McKenzie and Ward, 2012) to 1.6 million (Jacobs, 2004).

The maintenance of river water quality is controlled under the EU Water Framework Directive (2000/60/EC) for which waterbody-specific targets are stipulated in terms of ecological status. In England and Wales, the EA is the designated competent authority charged with monitoring, reporting and enforcement, while for Scotland it is SEPA, where the WFD is legislated under the Water Environment and Water Services (Scotland) Act 2003 (WEWS act). Identification of reasons for failure and programmes of measures to rectify non-conformity is undertaken in iterative cycles. Nationally around 75% of waterbodies currently fail to meet good ecological status although the situation is improving (Priestley, 2015). Urban influences may be dominant in governing the condition of waterbodies (e.g. effluents), especially in small waterbodies (McGrane et al., 2016). In this regard, control of hazardous substances through wastewater treatment and improvements to sewerage infrastructure are commonly implemented measures.

Climate projections for the UK are provided by the latest generation of the UK Met Office Hadley Centre regional climate model (RCM) projection scenarios − UKCP09 − and indicate the 21st C will have wetter, warmer winters (mainly to the north and west) and hotter, drier summers (mainly in the south and east) but with variable change predicted under emission scenarios and probability level (Murphy et al., 2010 − Fig. 1). This spatial and temporal variability across a relatively small island nation is not shown in global climate models (IPCC, 2014) and exemplifies why it is important to consider climate change at refined spatial and temporal scales using RCMs when assessing impacts on hydrological processes within relatively small (by international standards) catchments and defined urban areas.

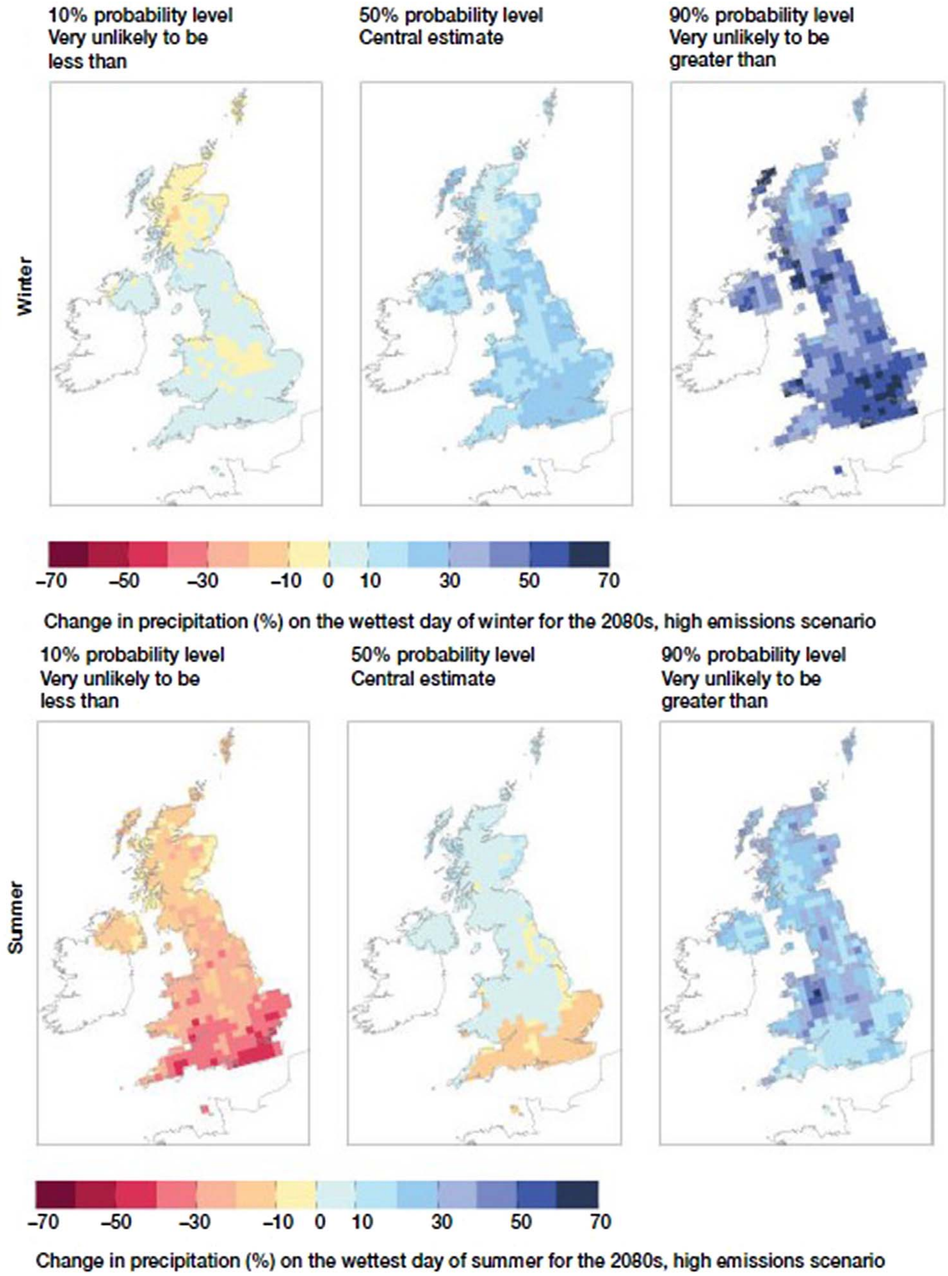

Fig. 1. UKCP09 projections of future change in precipitation under high emisions scenario (Murphy, et al. 2009).

3. Urban flooding: current and future pressures

3.1. Urban flooding: pluvial

3.1.1. Pluvial flooding and management

Pluvial flooding occurs when surface runoff generation exceeds infiltration rates and drainage capacity (Wheater, 2006), often during high-intensity short-duration (HI-SD) storm rainfall events. Drainage in the UK is designed to a capacity calculated by assessing the probable rainfall event of a certain AEP under a range of rainfall durations to assess the critical duration − being the storm that generates the highest peak flow. The UK Flood and Water Management Act (FWMA) 2010 sets current legislation and requires new developments to have surface water drainage plans with capacity for the 1% AEP rainfall event (Defra, 2011a,b) and the application of sustainable urban drainage systems (SuDS) to limit runoff to the natural 'greenfield' runoff rate (Defra, 2011a,b). The FWMA transfers responsibility for flood risk from central to local government, charging Local Authorities (LAs) and Lead Local Flood Authorities (LLFAs) with responsibility for pluvial flood risk (Begg et al., 2015).

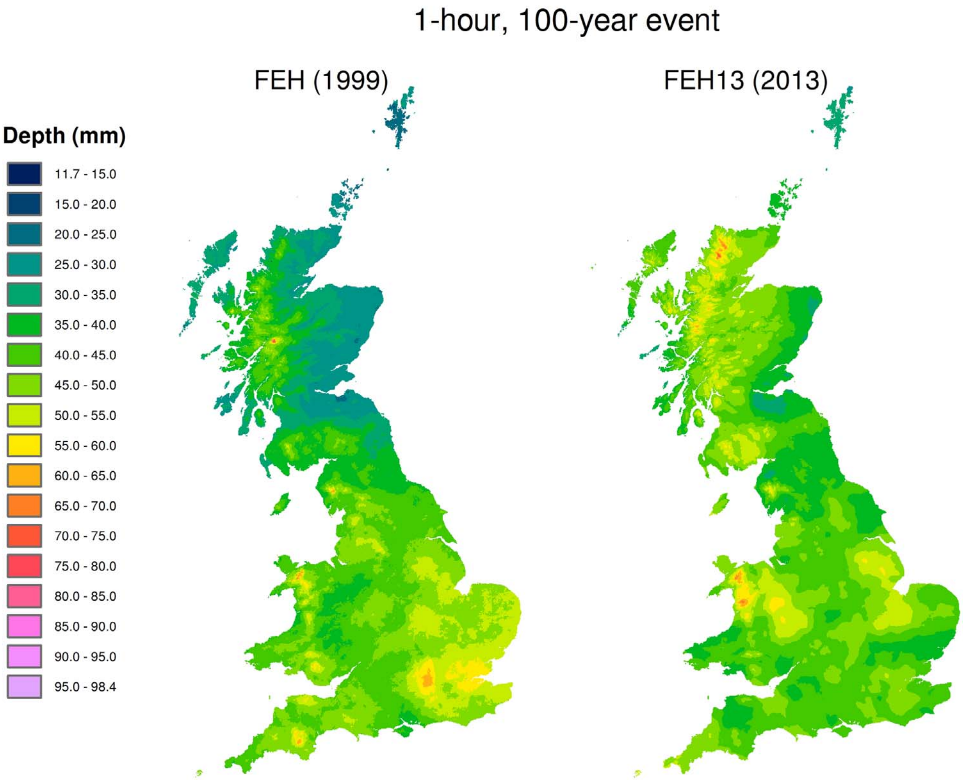

Fig. 2. FEH-DDF and FEH13-DDF 1-hour 100-year return period (RP) event rainfall for England and Wales (courtesy of Gianni Vesuviano, CEH).

Extreme HI-SD rainfall is highest in south-east England (Flood Estimation Handbook Depth-Duration-Frequency (FEH-DDF) model: Faulkner, 1999), however, recently improved raingauge coverage within an updated DDF model (FEH13-DDF: Stewart et al., 2014) has resulted in lowered estimates of the 1-h 100-year rainfall event for this region and higher estimates over Scotland and Wales (Fig. 2) (Stewart et al., 2015). These are important differences as such methods provide the baseline against which change in pluvial flooding can be assessed. Additionally, probabilistic approaches to estimate extreme rainfall are based on a stationary assumption at odds with trend analysis of some rainfall records (e.g. Jones et al., 2013), hence a growing body of international research has highlighted the need to develop and apply non-stationary models and frameworks (Milly et al., 2008; Hirsch, 2011; Cheng and AghaKouchak, 2014). Such non-stationary approaches are not utilized in current UK design flood rainfall methods but are being investigated (e.g. Prosdocimi et al., 2015).

3.1.2. Impact of urbanisation on pluvial flooding

Urban densification and inadequate urban drainage design have been primary drivers of pluvial and sewer flooding in the UK (Ofwat, 2011). While reported incidences of sewer flooding have been receding since the early 1990s due to increased legislation (National Audit Office, 2004) pluvial flooding has only recently been nationally assessed (EA, 2009) and is generally considered to have increased significantly with increased population (Pitt, 2008). Detailed estimates of UK pluvial flood risk indicate approximately 2 million people are exposed to a 0.5% AEP risk (Houston et al., 2011). During the 2007 UK floods EA figures suggest as many as two thirds of all flooding was attributed to inadequacies in surface water drainage systems (Pitt, 2008). In Northern Ireland much of the urban flooding experienced is due to HI-SD rainfall overwhelming ageing drainage systems (Rivers Agency, 2011).

3.1.3. Historical changes to extreme rainfall

Increases in frequency and intensity of extreme rainfall are physically consistent with global warming in the 20th C (Giorgi et al., 2011; IPCC, 2007) and borne out by trends at both global (e.g. increasing climatic extremes: Alexander et al., 2006) and regional scales (e.g. long-term increase in rainfall intensity identified across US: Kunkel et al., 2013). Yet, despite a wealth of hydro-meteorological records there remains insufficient evidence to conclusively link anthropogenic climate change to changes in UK observed precipitation records, with such cause and effect unlikely to become apparent until the 2050s (Fowler and Wilby, 2010). Evidence suggests: within-year clustering of extreme rainfall has recently increased; long duration summer events exhibit increased intensity (Jones et al., 2013), and; daily precipitation has become more intense in winter during 1961–1995 (Osborn et al., 2000). However, when set within a longer period of observations such patterns are less certain. Analysis of long historical periods has found no trend in annual average rainfall, however a weak winter signal has been identified (Jenkins et al., 2008). Additional urban heat island effects (Oke, 1982) that can increase mean precipitation (Shepherd, 2006) and initiate storm rainfall (Bornstein and Lin, 2000) have not been studied in the UK.

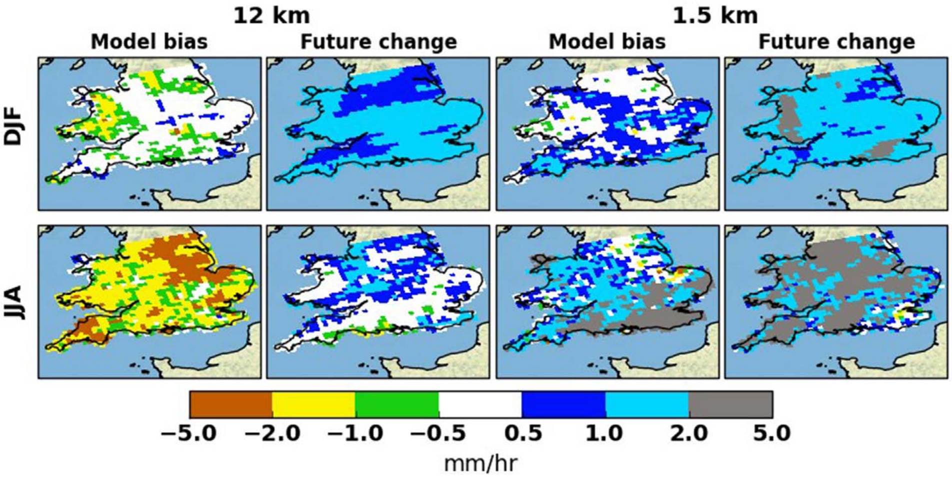

Fig. 3. Model biases and future changes to hourly rainfall (mm/h) in 12km and 1.5km climate models for winter (DJF) and summer (JJA) under high emissions scenario RCP8.5 (courtesy of Elizabeth Kendon, UK Met Office, and based on research in Kendon et al., 2014).

3.1.4. Future changes to precipitation and urban pluvial flooding

It is expected that a combination of future changes to rainfall, land use, and drainage design will render most large urban areas increasingly vulnerable to extreme rainfall and pluvial flooding (Willems et al., 2012). In the UK, current evidence is consistent with such international evidence, and indicates volumes and intensity of rainfall will increase by approximately 20% by 2085 (Ashley et al., 2008; Tait et al., 2008). Research using UKCP09 products indicates increasing intensity and severity of convective and frontal storms (Murphy et al., 2010), but Houston et al. (2011) argue that UKCP09 cannot provide robust and reliable results for maximum 1-h rainfall at high return periods as UK climate models do not produce robust projections of future rainfall at durations under one day. Strong advances in projected changes to future global rainfall intensity have been made (IPCC, 2012) but are limited to the daily scale, which given the relatively small scale of UK urban catchments is too coarse a temporal resolution. To resolve these limitations UK Met-Office (Kendon, 2014) applied a convection-permitting climate change model capable of simulating realistic hourly rainfall at a 1.5 km spatial resolution, including extreme rainfall. They found intensification of winter hourly rainfall and of summer short-duration events, and significantly more events that would cause flash flooding. The research highlighted significant differences in projected changes for summer hourly rainfall between the 12 km and 1.5 km models (Fig. 3). The 1.5 km RCM showed significant increases in HI-SD rainfall during summer (JJA) compared to results from the 12 km RCM that projected almost no change across the south-east. The ability to model future rainfall at this reduced spatial scale enables a more realistic representation of convective storms at a sub-daily time-scale (Kendon et al., 2014) and is clearly contrasting to results from UKCP09 (Fig. 2).

Modelling studies show that urbanisation and increasing rainfall intensity will increase drainage overflow volumes, resulting significant uplift (10% and 20%) to the 0.5% AEP event and more frequent and severe pluvial flooding (Tait et al., 2008; Abdellatiff et al., 2015). Houston et al. (2011) estimate such changes will cause 1.2 million more people to become exposed to pluvial flood risk from a combination of climate change (300,000) and population (900,000) by 2050. Ofwat (2011) considered the combined impact of urban creep (as derived by UKWIR, 2010), climate change (UKCP09–50th percentile) and population (ONS forecast for 2033), finding a median 51%, and mean 92%, increase in sewer flooding volumes by 2040. Financially the impacts are large, with the UK Climate Change Risk Assessment (CCRA) 2017 (Sayers et al., 2015) indicating a projected increase in expected annual damages (EAD) of 138% to £351 m by the 2080s. Comparison of these national assessments reveals significant discrepancy in the relative importance of population growth versus climate change in driving increase in pluvial flooding, Ofwat (2011) finding climate change to be by far the biggest driver, Houston et al. (2011) finding it to be population, and Sayers et al. (2015) finding broadly similar relative importance.

3.2. Urban flooding: fluvial

3.2.1. Fluvial flooding and management

Overbank (fluvial) flooding is a natural process essential for functioning river and floodplain ecosystems (Acreman et al., 2003) but evidence indicates that urbanisation can result in increased flood magnitude and frequency (Fletcher et al., 2013; Jacobson, 2011; Walsh et al., 2005). Within the UK there is a general move from traditional flood defences towards a flood risk management framework that is based upon more holistic approaches to flood management using natural solutions (Defra, 2012) as set out in FWMA 2010. However, the majority of risk is still managed through traditional defences, with £930 million spent during 2014–2015, and a further £180 million spent on maintenance (EA, 2014). The recent winter floods of 2015–2016 have highlighted the important role that traditional defences play while much of the subsequent discussion has centred upon the ability of more natural measures that reduce runoff, such as SuDS, to cope with such extreme events (Priestley, 2016).

3.2.2. Urbanisation and fluvial flooding

Evidence for the impacts of urbanisation on fluvial flooding in the UK is not as robust or prolific compared to international evidence (e.g. Braud et al., 2013; Burns et al., 2005; Sheeder et al., 2003; Sheng and Wilson, 2009) but early empirical studies in the UK (e.g. Hall, 1977; Hollis, 1975; Hollis, 1988; Hollis and Ovenden, 1988) certainly provide consistent evidence that urbanisation results in increased flood magnitude and frequency. Such data form the basis of hydrological models that have since become the de-facto tool for determining the hydrological impacts of urbanisation (Praskievicz and Chang, 2009; Salvadore et al., 2015). At the sub-catchment scale, Miller et al. (2014) found the transition from rural to peri-urban significantly increased flood magnitude and reduced catchment response times. Non-stationary statistical analysis of peak flow data from two paired urban and non-urban catchments showed the magnitude and frequency of extreme flood events have increased with urbanisation (Prosdocimi et al., 2015). A regional scale study of the Thames basin undertaken by Crooks and Kay (2015) showed urbanisation since the early 20th C has altered the rainfall-runoff response and increased summer flows. The reality however becomes much more complicated with increasing scale, and Wheater (2006) finds while urbanisation might represent a significant increase in flooding for small catchments, at larger scales the effects are highly complex and a result of sub-catchment responses and mitigation measures.

3.2.3. Climatic changes and high flows

Despite a good history of river gauging across the UK, Hannaford (2015) finds that observed changes in peak flows cannot be directly attributed to climate change as records are limited and trends are affected by natural variability. The only event-based attribution undertaken assessed the autumn 2000 flood event, finding that anthropogenic emissions of greenhouse gases are likely to have led to an increased probability of flooding (Kay et al., 2011). Similarly, the IPPC found only with low confidence can it be concluded that anthropogenic climate change has affected flood frequency and magnitude due to absence of links between climate change and high flows and lack of suitably long-term records (IPPC, 2014).

3.2.4. Future changes to urban fluvial flooding

A legislative requirement (FWMA, 2010) to undertake detailed local town-city scale strategic flood risk assessments delivers some clarity on how local development will impact upon fluvial flooding, but at a national scale there is a lack of detailed assessment. In one national assessment focused on ecosystem services Eigenbrod et al. (2011) found that by 2031 under a densification scenario some 1.7 million persons will neighbour rivers showing an increase of at least 10% in peak flows, whereas only 11,000 would be affected and peak flows would barely rise under a sprawl scenario. No studies were found that make use of real-world urban projection scenarios, despite the large population increases discussed.

While research into urbanisation and urban flooding at national scales is lacking, impacts of climate change on river flows are better studied and represented in guidance − albeit based on predominantly non-urban research. A national 20% uplift value for climate change was derived from modelling on the predominantly rural Thames and Severn catchments (Reynard et al., 1999). Reynard et al. (2017) find this to now be well incorporated and implemented in national floodplain modelling, but find more recent regional allowances present practical challenges in how local planners interpret such figures without detailed flood modelling. Reviewing the literature, Arnell et al. (2015) identified considerable uncertainty exists but that flow regimes will change and different catchments types will respond contrastingly to the same climate scenario. Relevant to UK urban systems, research using UKCP09 projections indicates small increases in winter flows (Christierson et al., 2012) driven by raised winter precipitation (Charlton and Arnell, 2014), and, in the Thames basin by the 2080s, variable increases in flood peaks at the 0.2% AEP (Bell et al., 2012). More detailed analysis can be undertaken using the high resolution 1.5 km RCM developed by Kendon et al. (2014), with Kay et al. (2015) showing projected changes to future seasonal peak flows using the CLASSIC-GB hydrological model. Fig. 4 illustrates the seasonal differences in percentage change in annual and seasonal peak flows between the 12 km and 1.5 km RCMs for a range of return periods. The least difference in percentage change between the 12 km and 1.5 km RCMs at higher return periods is observed for summer peak flows, contrasting with the findings of Kendon et al. (2014) whereby the largest difference in HI-SD rainfall is projected to be in summer (Fig. 3), however there is a greater difference at lower return periods. Kay et al. (2015) state this is due to the minimum catchment scale being 50 km^2 and thus larger than many urban catchments where changes to sub-daily rainfall intensity would have a much larger, and less attenuated, impact. This highlights that even with refined precipitation projections there is an additional requirement for high-resolution modelling to capture the scale of urban systems.

Future changes in urban river flooding will ultimately be the result of interactions between management interventions with climate and urbanisation drivers (Wheater and Evans, 2009). Determining relative and cumulative impacts is difficult, and dependent on economics, given the need for cost-benefit analysis before implementing flood defences. Various national flood risk analyses predict big increases in economic risks by the 2080s attributable to a combination of climate and socio-economic changes (Hall, 2003; Evans et al., 2004; Sayers et al., 2015). But there is still an overall lack of nationally focused hydrological research that considers the combined pressures of climate change and urbanisation, from which to develop detailed national understanding of future flooding in UK urban areas.

3.3. Urban flooding: groundwater

3.3.1. Groundwater flooding and management

Groundwater flooding in urban areas is driven by a number of different hydro-climatic and water management scenarios (Macdonald et al., 2008). Management of such flooding is problematic, as evidenced for example by the unprecedented groundwater flooding of 2000–2001 (Marsh and Dale, 2002), and while agencies such as the EA have oversight, there is little they can do except to provide planning advice such as indicating probable flood risk zones.

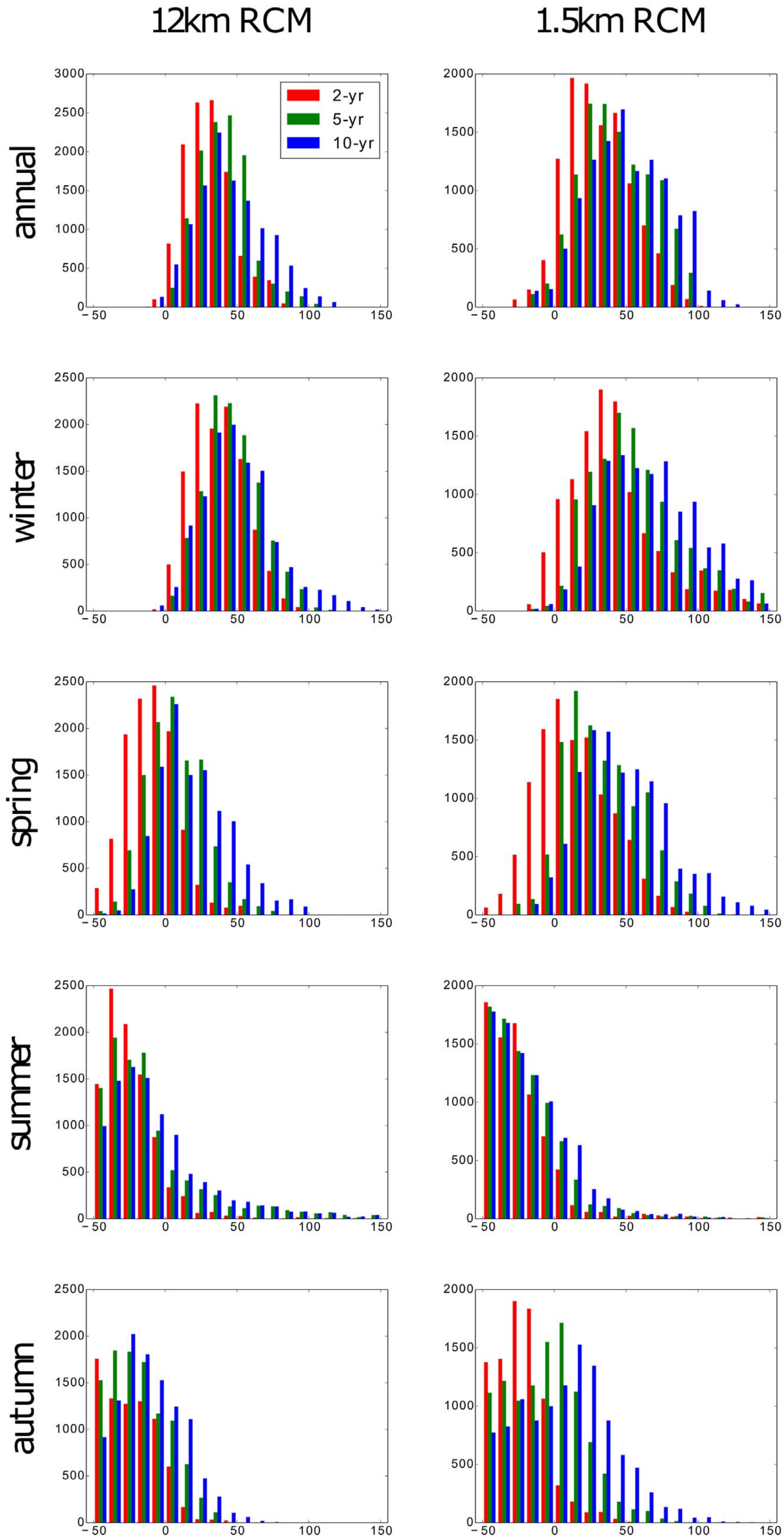

Fig. 4. Percentage change in 2- 5- and 10-year return period flood peaks between current and future time-slices, for 12 km RCM and 1.5 km RCM (courtesy of Alison Kay, CEH, and based on research in Kay et al., 2015).

3.3.2. Historical changes to groundwater flooding

A recent review of groundwater levels (Jackson et al., 2013) found no evidence for systematic alterations of groundwater drought frequency or intensity. They did uncover evidence of multi-annual to decadal coherence between groundwater levels and climate, however it is uncertain what role land-use change might have played. Overall, evidence attributing long-term changes in urban groundwater flooding to either urbanisation or climatic change was found lacking (Jackson et al., 2013).

3.3.3. Future groundwater flooding

Literature assessing the potential impacts of future urbanisation and climate change on groundwater flooding in the UK is limited and uncertain. There is limited evidence suggesting urban development could raise flood risk, as shown by Macdonald et al. (2012) in Oxford. There is similarly limited research into the impacts of climate change on groundwater flooding, with most studies suggesting agreement that recharge and levels will decrease, indicating a reduced risk (Herrera-Pantoja and Hiscock, 2010; Jackson et al., 2011; Jackson et al., 2013). A recent assessment of future groundwater flood risk (excluding population growth) indicated 71% and 90% increases in significant chance of flooding for residential and non-residential properties respectively by the 2080s (Sayers et al., 2015). Given the large population growth forecasted it is likely such figures would be elevated if population growth and new development was also factored in.

4. Urban water quality: current and future pressures

Urbanisation degrades water quality through three primary mechanisms: i) discharge of pollutants at point sources and mobilisation of pollutants from diffuse sources; ii) flow alteration; and iii) changes to the temperature of receiving watercourses. Each of these will be affected by the form and function of future urbanisation, and its associated controls and management of potential pollutant discharges. Additional stress will be placed on receiving watercourses from changes to climate through alterations to rainfall and temperature and resultant changes in bio-physical properties.

River water quality, both chemical and biological, was until 2009 monitored and assessed using the General Quality Assessment (GQA) scheme. Data showed a general improvement (Fig. 5) in rivers exhibiting good or excellent chemical and biological quality (EA, 2013). Since 2009 the classification scheme introduced by the Water Framework Directive (WFD) standards have been in place, and in 2009 26% of water bodies in England met Good Ecological Status (the requirements for viable ecosystems), decreasing to 25% in 2012. Whilst significant effort has been made in reducing agricultural, point source and industrial pollution there remains increasing pressure from urban diffuse pollution which is responsible for 49% of failures to water quality targets (Defra, 2012). Major pollution events in UK urban rivers are primarily a result of partially treated sewage being discharged during storm events (Ellis, 1991).

4.1. Urban water quality: point and diffuse source pollution

4.1.1. Point source: treated

Despite improved waste water treatment the majority of the phosphorus load is attributable to household and industrial sources (White and Hammond, 2009), with effluent discharges accounting for 50% of annual P loading in a typical urban catchment (Halliday et al., 2015). Advanced P treatment at sewerage treatment works (STWs) is becoming more commonplace and evidence from monitoring across the Thames shows significant reduction in orthophosphate (Kinniburgh and Barnett, 2010) and SRP (dissolved monomeric inorganic phosphorus) downstream of urban areas and STWs (Jarvie et al., 2002). However this can vary, with other catchments exhibiting an increase (Neal et al., 2008). Nitrogen loads, whilst having a greater proportion from agricultural sources, are dominated by fluxes from treated effluent in dry periods (Causse et al., 2015).

4.1.2. Point source: untreated

Morrison et al. (1984) estimate that of the annual pollutant load into UK receiving waters 35% came from point source combined sewer overflows (CSOs) and polluted surface water outfalls (PSWOs) operating only 2–3% of the time. A particular legacy of older UK cities, such as London, are the large number of misconnections and lack of capacity in older sewers leading to frequent foul water contamination of urban watercourses (Faulkner et al., 2000). Such discharges are found to impair receiving waters contributing high loads of a wide range of pollutants most notably microbial pathogens, biochemical oxygen demand (BOD) and suspended solids (Abdellatif et al., 2014). Of the BOD, sediment and nutrient CSO load at least half (50–60%) is attributable to in-pipe scour (Mulliss et al., 1996) in the form of frequent fluxes that additively affect ecology of receiving waters, with chronic impacts distinguishable downstream. While the focus has historically been around sediments, organic matter, heavy metals and nutrients, more recently interest has grown concerning pathogens and emerging priority pollutants such as industrially derived components of the type listed under the WFD (Fletcher et al., 2013) and nanoparticle pollution (Dumont et al., 2015). Summarising water quality data collected for eastern UK rivers draining to the North Sea, Neal and Robson (2000) find major, minor, nutrient and trace elements in urban and industrial rivers that reflect the importance of point source pollutants; for soluble chemical species, urban and industrial concentrations are higher in summer months due to reduced dilution in lower flows. Regulation and treatment technology is proving increasingly effective at limiting such point sources and the GQA scheme previously used to monitor rivers across the UK (Defra, 2010) showed improvements, particularly in chemical water quality in England (Fig. 5).

4.1.3. Diffuse urban pollution

Diffuse pollution is derived through mobilisation of accumulated polluted sediments during first-flush events (Sansalone and Buchberger, 1997) and over prolonged periods (Lawler et al., 2006). Nearly one third of pollution incidences within the Thames Region are attributed to diffuse urban pollution and include pollutants coming from a range of sources including residential runoff, commercial/

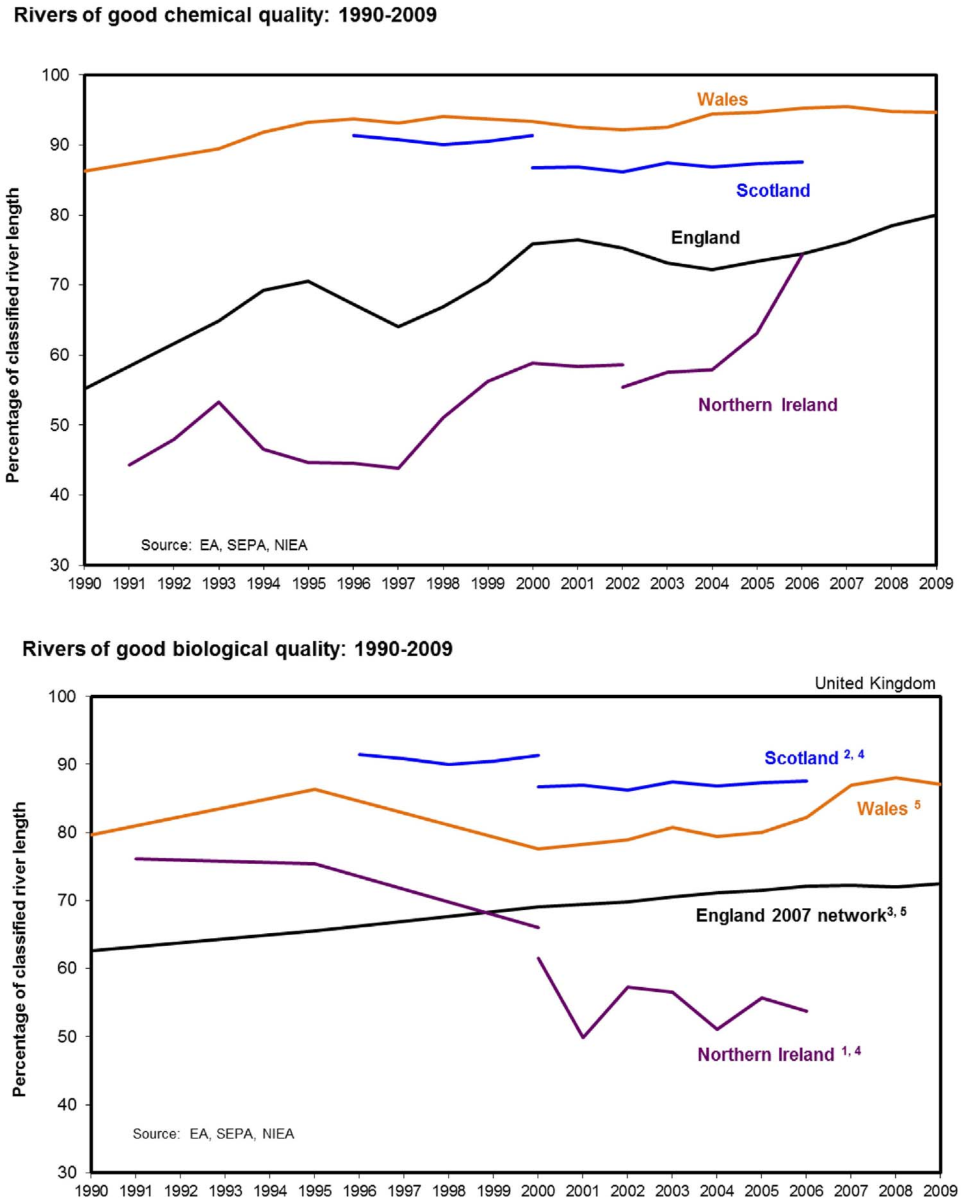

Fig. 5. Water quality in UK. Obtained from ttps://www.gov.uk/government/uploads/system/uploads/attachment_data/file/141707/rwisd2009annresults.xls.

industrial runoff, construction, vehicle emissions, and leaking sewer pipework (as distinct from CSOs) among others (Ellis and Mitchell, 2006). Of these, Lundy et al. (2012) report that construction sites and residential runoff provide the primary sources of sediment, whereas misconnections are important for P and ammonium (NH4), and fertilisers also contribute to NO3 loads. In the UK oil and hydrocarbon diffuse pollution of urban watercourses constitutes up to 17% of all reported water pollution incidents, originating primarily from industrial areas and highways (Ellis and Chatfield, 2006). D'Arcy et al. (2000) identify urban diffuse pollution being responsible for 11% of polluted Scottish rivers and the downgrading of around 4–5% of rivers in England and Wales, while Ellis and Mitchell (2006) note that the reality may be far worse given the lack of sufficient monitoring to identify diffuse urban pollution. The delivery of diffuse pollutants to watercourses is directly influenced by the presence of stormwater management infrastructure, such as retention ponds, which have been shown to decrease sediment, nutrient and dissolved organic carbon (DOC) delivery (Hale et al., 2014). While there have been some event-based testing of bio-retention ponds in the UK (e.g. Hares and Ward, 1999; Shutes et al., 1997) and modelling to quantify their impact (Quinn and Dussaillant, 2014) there have been no long term tests on such systems.

4.1.4. Impact of population growth on pollutant loading of urban rivers

While a range of future population projections exist (ONS, 2013) these have not been translated into spatially explicit assessment of urban pollutant loading impacts. Beyond population alone there is also a growing threat from uncontrolled substances, such as nano-particles (Dumont et al., 2015) or steroid oestrogens (Keller et al., 2015) that are causing unknown damage to the environment,

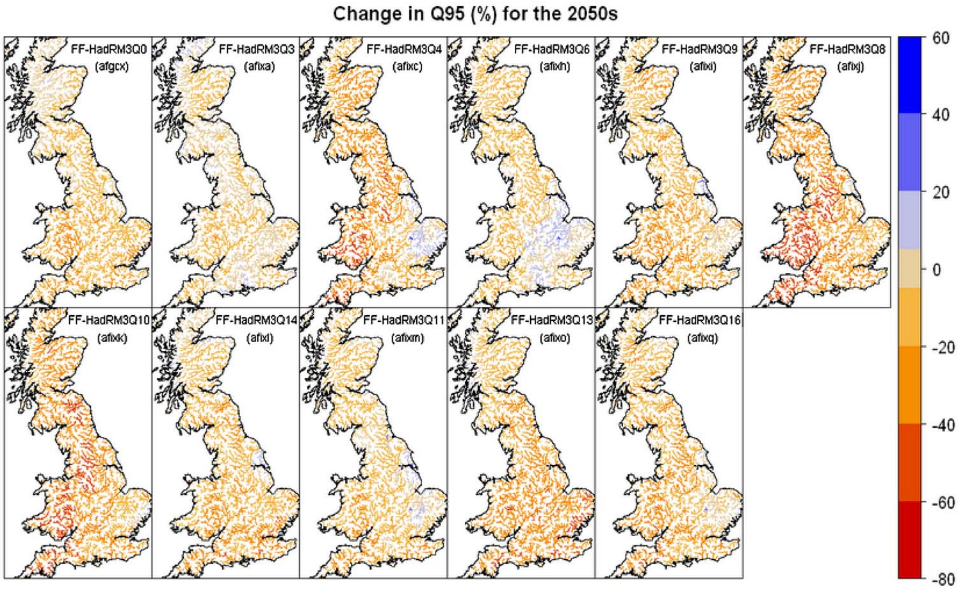

Fig. 6. Changes in Q95 for 2050s from CERF driven by Future Flows Climate changes (Copyright NERC: contains Ordnance Survey data @ Crown Copyright and Database Right).

are not routinely sampled, and in many cases are becoming more prolific in utilization.

4.1.5. Additional impacts of climate change

The majority of climate change impacts research within the UK has focused upon catchments with issues of agricultural diffuse (e.g. Macleod et al., 2012) and mining pollution (e.g. Foulds et al., 2014). Of those assessing urban areas, most do so indirectly through the study catchment location. Modelling of the Thames basin, with large urban areas, using the Future Flows projections for river flow (Prudhomme et al., 2012a) and the water quality model Questor, Hutchins et al. (2016a) found reduced low flows (Q95) and an increase in the number of days violating water quality criteria for dissolved oxygen (DO), BOD and Chlorophyll. Other studies highlight the combination of climate change and urbanisation will increase the frequency and magnitude of events exceeding threshold DO and NH4 concentrations, primarily through increases in rainfall depth rather than intensity, and with urbanisation impacts driven by projected increases in per capita water consumption and more uncontrolled discharges (Astaraie-Imani et al., 2012; Whitehead et al., 2013).

4.2. Urban water quality: flow alteration

4.2.1. Urban flow regime and water quality

The impacts of urbanisation on urban flow regime, as observed in UK catchments, includes reduced low-flows and baseflow (Hollis, 1975), increased stormwater flows (Hall, 1977), and increased dry weather flows from effluent discharges which are typically diurnal in pattern (Halliday et al., 2015). Increased dry weather flows will directly bring about higher pollutant concentrations at low flow due to lack of dilution (Keller et al., 2015) and might constitute a transfer of water into the river catchment (Lawler et al., 2006). However, adverse water quality changes (increased nutrient, toxicant fluxes and higher temperatures) are also likely to occur in response to hydrographic and morphological alteration but are hard to disentangle from changes to exposure to pollutants (Walsh et al., 2005). While there is a general lack of empirical observations linking urbanisation and flow regime in the UK, those limited studies are consistent in suggesting sewage effluent contributes a significant proportion of dry weather low flows in urban watercourses, driving a diurnal fluctuation in river flows.

4.2.2. Historical changes in flow regime

To determine impacts of historical climate change on flow regime requires assessment of near natural 'benchmark' catchments as UK urban catchments are so heavily modified any trend would be masked (Hannaford, 2015). In a national assessment of low-flows using the UK Benchmark network Hannaford and Marsh (2006) found no conclusive evidence of change in Q90 from the 1960s to early 2000s, a finding echoed in later work by Marsh and Dixon (2012) assessing trend in Q95.

4.2.3. Future urban flow regimes

Despite a wealth of research into climate change impacts on UK river flow regimes using UKCP09 projections (Charlton and Arnell, 2014; Christierson et al., 2012; Remesan et al., 2013; Bell et al., 2012) there are no targeted studies on flow regimes in urban areas. Studies using UKCP09 projections all point to reductions in flows, particularly in summer months. The Future Flows and Groundwater Levels project (Fig. 6) suggests lower summer (June–August) flows across Britain (Prudhomme et al., 2012b) under almost all scenarios. Future changes in flow will further impair urban river quality.

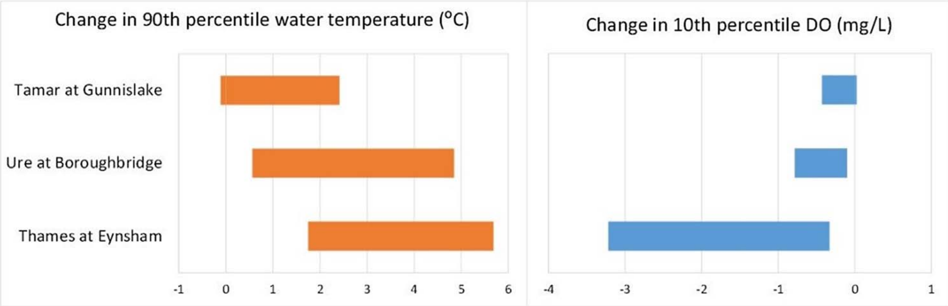

Fig. 7. Future change in river water temperature and dissolved oxygen (DO) relative to present day conditions. These are displayed as a confidence interval based on multiple simulations of a chained model application, driven by regional climate model projections, comprising Future Flows Hydrology (Prudhomme et al., 2012b) and QUESTOR (Hutchins et al., 2016a). Summary statistics are based on a comparison of model output from two 30-year periods representing present day and future (2050s) conditions.

4.3. Urban water quality: river temperature

4.3.1. Urbanisation and river temperature

Despite water temperature being an important regulator of freshwater ecosystems, measurement of water temperature in the UK has not been undertaken at the spatial and temporal resolution of air temperature, which itself is not a direct indicator (Hannah and Garner, 2013). The mechanisms for raising water temperatures in urban areas include large scale discharges from sewage treatment works, industry and power plants, along with domestic discharges and even warming resulting from runoff over paved surfaces (Herb et al., 2008). While there are clear linkages demonstrated in international catchments between urbanisation and water temperature (e.g. Kaushal et al., 2010; Klein, 1979) there is limited specific evidence within the UK and none for urban areas (Webb and Walsh, 2004).

4.3.2. Evidence of climate driven changes in river temperature

In a recent review of the literature (Hannah and Garner, 2015) found historical evidence that temperatures have increased in the latter 20th C but low agreement on the attribution of change to climatic warming. In one of the more complete studies Orr et al. (2014) found a slight increase in mean water temperature and positive changes at 86% of all 2773 sites, and inferred that climatic changes are driving the observed trend. No specific temperature data has been assessed for urban watercourses.

4.3.3. Future urban river temperature

Modelling studies of UK catchments show increases in temperature and reductions in dissolved oxygen (DO) (Fig. 7) also being identified by others (e.g. Cox and Whitehead, 2009). For future water temperature in the UK there has been no attempt to explicitly model the impacts of future urbanisation, and Hannah and Garner (2013) indicate few predictive studies of climate change impacts on UK rivers exist. Reviewing the evidence for UK water temperatures in general they found some agreement that UK river temperatures will increase, but that due to interlinked uncertainty future estimates are beyond current knowledge. Using earlier UKCP02 projections, Webb and Walsh (2004) found future warming leads to an increase in UK river temperatures, with significant variability between sites being moderated by catchment characteristics.

5. Confidence assessment of evidence

This section provides a confidence assessment of the reviewed literature in providing evidence of a direction of change or response in urban flooding and urban water quality as a result of urbanisation and climate change. In order to assess the confidence of reported projected changes a level of confidence has been ascribed to the overall direction of change for each topic (Table 1). This is based upon a confidence matrix that reflects both the amount of evidence and the degree of agreement. Such confidence assessments were developed and employed when evaluating evidence in the IPCC AR5 (Mastrandrea and Field, 2010) and climate change impact report cards for the UK (e.g. Hannah and Garner, 2013). Topics assessed as having HIGH confidence evidence are those with numerous sources of evidence with results in agreement, MEDIUM confidence is ascribed where there is limited evidence but results are in agreement, while LOW confidence is ascribed where only isolated or inferred evidence was available. The confidence ascribed should only be taken as indicative of the state of current knowledge and direction of change, not the quality of evidence. For such an assessment a systematic review would be required.

The confidence assessment reveals high variability in the confidence ascribed. Pluvial flooding has generally high confidence ascribed to the evidence on the impacts of urbanisation and climate change, particularly when combined, all pointing towards increases in flooding. The evidence for urbanisation and climate change driving increased fluvial flooding is ascribed an overall medium level of confidence, but with low certainty on the impacts of climate change in urban areas. Groundwater flooding evidence is very limited and uncertain in direction, and found to be generally of low-medium confidence. Increases in point source pollution as a result of both pressures were found to be generally high confidence, while evidence on diffuse pollution was found to lacking.

Table 1
Confidence assessment of evidence on future direction of change/response in urban flooding and water quality as a result of urbanisation and climate change using evidence considered in this review. Green (bold text) indicates HIGH confidence, Yellow (italics) MEDIUM confidence, and Orange LOW confidence. Direction of future change/response is indicated as: ↑ = increase, ↓ = decrease, ↕ = increase and decrease, mgmt = management, P = precipitation). (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article.)

	Direction of future change/response			
Feature	Urbanisation	Climate change	Combined	Limitations/Uncertainty
Pluvial/sewer flooding	*↑ Impervious cover*	*↑ Rainfall intensity*	**↑ Overflow volumes**	Mgmt – SuDS, Scale
	↑ Urban creep	**↑ Rainfall amount**	**↑ Property flooding**	Location/Season
	↑ Population	**↑ Wetter winters**	**↑ Population affected**	Relative impact
	↑ Surface runoff	*↑ Winter events*	**↑ Sewer flooding**	Urban design
		↑ Frequency		Baseline data
		↑ Extreme summer P		Models/Scenario
		↑ Basement flooding		Region
		↕ Summer events		
Fluvial flooding	**↑ Flood risk**	*↑ Flood risk*	**↑ Flood risk**	Mgmt - defence
	↑ Flashy response	*↑ Annual peak flows*	*↕ Flooding*	Catchment/ CC scenario
	↑ Flood frequency	*↑ Flood frequency*	*↑ Flood frequency*	Baseline data
	↓ Natural mitigation	*↑ Winter high flows*	**↑ Economic costs**	Region
	↑ Densification	↕ Summer high flows	*↑ Population affected*	Climate data/ scale
		↑ Volumes		
Groundwater flooding	↓ Infiltration	*↓ Groundwater levels*	↕ Groundwater floods	Inference
	↑ Flood risk	*↕ Flood risk*		Baseline data / Location
		↓ Recharge		Time frame / model
Point source pollution	*↑ Pollutant loading*	**↓ Dry weather flows**	**↑ Concentration**	Mgmt – STW treatment
	↑ Pollutant loading	*↑ HI-SD P events*	*↑ Discharges*	Climate data/ scale
	↑ Water consumption	**↑ Precipitation**	**↑ Ammonium ↓ DO**	Projected consumption
Diffuse pollution	*↑ Urban surfaces*	*↑ Dry weather flows*	↑ Pollutant flushing	No direct evidence (UK)
		↑ P intensity		
Flow regime	*↓ Low flows*	**↓ Low flows**	*↓ Pollutant dilution*	Season/ Treatment
	↑ Low flows (STW)	**↓ Annual flows**		Future treatment
	↑ Flashy response			Location
River temperature	*↑ Temperature*	*↑ Temperature*	*↑ Temperature*	Urban data/ science
	↑ Diurnal fluctuation	*↑ Temperature*	*↓ DO*	Catchment

Evidence of flow regimes points towards some uncertainty over the impacts of urbanisation, however there is high confidence that climate change will drive lower flows, but the combined impacts have not been robustly assessed. River temperature evidence was ascribed medium confidence and indicates an increase with both urbanisation and climate change. In summary there is an overall lack of high confidence evidence and particular deficiencies on certain topics are covered in the discussion.

6. Discussion – managing the urban water environment in the future

6.1. Future urban flood risk management

The science on future flooding in the UK literature is found to be generally consistent and to provide medium-high confidence of evidence that urban pluvial and fluvial flooding are set to increase through both drivers, with a low certainty regarding changes to groundwater flooding. National policy is found to generally reflect the evidence base and, while not yet regionally focused, provides suitable national values for flood risk management (Reynard et al., 2017). For example, UK storm drainage design methods employ a 30% uplift of rainfall intensities to DDF estimates when considering the 1% AEP – accounting for both climate change to 2085 (20%) and an 'urban creep' factor of 10% (EA, 2013a). Thus the evidence has clear utility for setting recent UK policy and technical guidance such as *Planning Policy Statement (PPS) 25* in providing quantitative consideration of climate change and urbanisation, here through application of the recommended national precautionary sensitivity ranges listed in guidance for planning of new developments (FCDPAG3: Defra, 2006).

More of a concern, given the findings of this review, is that figures put forward for use in planning for urban pluvial and fluvial flooding remain generic and that there is an overall lack of nationally focused research into the combined pressures of rapid urbanisation and climate change. The lack of national scale assessments limits the ability to strategically plan mitigation or urban development and design effective flood management − particularly to inform the location of new towns. Similarly, the evidence suggests high spatial and seasonal variability in the degree of change, particularly between catchments, limiting the application of findings from one urban centre to another. For example, while localised flood risk assessments are carried out there is a lack of suitable climate model precipitation outputs and consideration of uncertainty. This backs up earlier reported findings from Prudhomme and Reynard (2009) in assessing the FCDPAG3 guidance that seasonal and regional variation are more appropriate and that the ranges provided are precautionary. An additional concern from this review is the lack of evidence or policy concerning groundwater flooding which could prove an additional pressure that is not fully understood. Taking an holistic view of all three flooding sources the CCRA 2017 assessment Sayers et al. (2015) suggest current levels of adaptation are not sufficient to offset projected increases in flood risk under 2–4 °C climate change projections and that a 'whole system' approach to adaptation is required.

This review has highlighted the lack of non-stationary approaches for designing DDF curves and estimating flood rarity in a changing climate. This has serious implications for the design and management of urban drainage and flood defence in the UK. International research points towards reductions in the rarity of current DDF curves (Willems and Vrac, 2011) and therefore more frequent 100-year floods (Vogel et al., 2011; Villarini et al., 2009). This implies that design of urban drainage or flood defence set out at current estimates will be more frequently exceeded and that storms with higher return periods will be required for use in design of future proofed systems.

Much of the UKs future mitigation of flood risk is based around 'hard' engineered flood defences with two complementary but very different approaches. The first is to ensure natural 'greenfield' runoff rates are maintained through SuDS features (FWMA, 2010). However, these methods require further calibration and testing in urban catchments and are based on stationary assumptions (Faulkner et al., 2012) contrary to international evidence (Milly et al., 2011; Stedinger and Griffis, 2011). The second form of mitigation is set out in the government strategy *Making Space for Water* (Defra, 2005) which advocates a catchment based holistic approach, focused upon increasing resilience, and incorporating an allowance of risk (Wilby et al., 2008). More recent flooding has stimulated a Government inquiry into the efficacy of natural solutions for extreme events following the winter 2015–16 floods and the possible need for further investment in hard defences (Priestley, 2016).

Given the clear messages in the evidence and policy regarding increased future flood risk as a result of climate change and urbanisation this raises concerns over how realistic is it to keep building hard defences that will inevitably be overtopped or to incorporate risk allowance where risk is continually increasing. It also brings into focus the concern as to whether society can ever rely on natural approaches given the uncertainty concerning their efficacy in large storms? To resolve such questions in the face of continued population growth more urban focused science is required, using suitable climate products such as the high resolution (< 5 km) RCM runs being developed for UKCP18. Such science further requires translation into policy for it to be applied, and Reynard et al. (2017) find more effort is required to distil complex science into information digestible by policy-makers to ensure policy reflects evolving science and its uncertainty.

6.2. Future urban water quality management

A good sized body of evidence on the impacts of urbanisation and climate change on urban water quality in the UK has been found for point source pollution and flow regimes, but lacking for diffuse pollution and river temperature. What is most clear is that a combination of increased pollutant loading from a greater population and urban area combined with reduced dry weather flows will increase pollutant concentrations. Less clear is how an increase of urban surfaces will combine with climatic changes such as intensity and frequency of storms to affect diffuse pollution entrained in first flush events. The evidence for temperature, while not found to be of high confidence, all points towards raised temperatures as a result of both urbanisation and climate change, resulting in lowered DO.

There is an inherent complexity in attributing future water quality to climate change in urban areas, as the source management of pollutants plays a particular role. For example, despite evidence of recent increased warming in the UK, observed changes in invertebrate communities were found to be driven by improvements to water quality rather than any climatic shifts (Vaughan and Ormerod, 2014). Changes occurring will be affected by point and diffuse pollution management and the relative impacts of climate change on future water quality in urbanising basins may be small (Cox and Whitehead, 2009). Wilby et al. (2010) identify management will be defined by a range of desired outcomes and regulations that includes targets set by regulators adhering to WFD status, conservationists seeking to reverse biodiversity loss, and water managers balancing the twin needs of meeting supply within a changing climate and meeting statutory obligations.

There is a growing desire for increasingly integrated water management planning, through catchment based approaches and alignment of flood risk and river basin management (e.g. FWMA 2010; Defra, 2013), but little consideration of the utility of available evidence to inform such decisions (Ross et al., 2015). The literature reviewed here has shown a medium-high confidence that both urbanisation and climate change will result in negative changes to urban water quality and increased flood risk. Thus at the policy level, where this debate remains, it would seem there could be clear benefits in aligning planning measures to manage water use and reduce urban runoff. Such policy development should consider such inter-relationships between the changes identified in Table 1 and acknowledge both urbanisation and climate change as causal drivers of change that need to be accounted for in providing effective planning integration.

Another key area under which the utility of evidence concerning future water quality is under particular scrutiny is the WFD − particularly in light of possible legislative changes resulting from Brexit. There has been considerable debate as to how best to measure the status, and despite time-scales that extend well into the future there is no explicit consideration of climate change (Wilby et al., 2006) or the real-world pressures of population growth, new pollutants and diffuse pollution. Such uncertainties make it problematic to define the status of such modified water bodies and to set improvement targets that do not incorporate the benefits of modification such as flood defence and water storage. Recent guidance from the UK Technical Advisory Group on the WFD (UKTAG) has highlighted this by proposing the aim for such heavily modified water bodies (HMWBs) is to achieve good ecological potential (GEP) − being the quality achieved without adverse impacts on other modified benefits (Uktag, 2013). At present that information is not available and the scale and cost of implementing such a large directive certainly requires evidence of more utility in urban areas. However, advances in technology (e.g. optical- and fluorescence-based sensors) could enable improved understanding of urban water quality and ongoing monitoring strategies should be underpinned by technological developments. Such technology in a post-Brexit UK poses opportunities for research to reassess how best to ensure improved water quality and set out possible new forms of legislation.

6.3. Barriers to sustainable and effective adaptation

The uncertainties on how future climate will alter physical, chemical and biological systems, combined with further uncertainty arising from climate models and future water management, currently limits our ability to provide robust predictions and identify how best to manage the water environment (Whitehead et al., 2013). Much of this uncertainty is attributed by Arnell et al. (2015) to a lack of understanding about how the components of the water environment interact, compounded by high uncertainty in climate science and how future water management will evolve. The particular complexity of urban water systems, such as managing demand and supply while also protecting for floods, and the uncertainty surrounding the impacts of significant population growth, are all significant barriers to sustainable and effective adaptation for the UK. Successful management will need to adapt to a developing scientific understanding of how climate change and urbanisation impact the urban water environment. Programmes such as NanoFATE (Dumont et al., 2015) and POLLCurb (Hutchins et al., 2016b) are suitable platforms for collaborative research, but more effort is required to foster successful dialogue with policy-makers to translate the science and overcome current barriers.

7. Conclusions and knowledge gaps

This review has shown there is a large body of literature on the impacts of climate change on UK flooding and water quality but that specific literature on urban areas and urban impacts is less well covered, and specifically that the combined pressures are less researched. For pluvial and fluvial flooding, and point-source pollution and flow regime, the evidence is generally of medium-high confidence in showing the combined pressures will result in increased risk of flooding and degradation of urban water quality. Policy is found to reflect this evidence at a national scale, but requires more refinement to represent regional variability and scientific uncertainty. There are some areas however, notably groundwater flooding and urban diffuse pollution, where evidence is lacking and was ascribed of low-medium confidence that the combined pressures will alter groundwater flooding or increase diffuse pollution. This limits Government ability to set out evidence-based policy and requires focused research guided by policy needs.

Despite being a relatively small developed nation, with policy that reflects the broad scale direction of change and impacts that urbanisation and climate change pose, high spatio-temporal variability and uncertainty in climate and rapid population growth raises serious questions concerning how the UK can design future climate-proof cities and whether evidence is fit-for-purpose when setting future planning policies or designing infrastructure. Both urban flooding and water quality face a number of pressing concerns and knowledge gaps that includes: the impacts of urban densification and expansion; population distribution; regional changes in storm rainfall intensity and frequency; incorporating uncertainty and science development into policy; incorporating non-stationarity. And research in both areas is hindered by a lack of suitable models to represent the complexity of managing water in the urban environment. Urban water quality faces its own challenges, particularly when considering the implementation of the WFD and unknown system responses to climate change and urbanisation, along with threats posed by emerging pollutants and diffuse urban pollution.

While broad scale regional differences in changes to seasonal rainfall have been provided in products such as UKCP09, only now are suitable scale climate products being developed to provide projections of how rainfall intensity, convective storms, urban flooding and first flush events might change in the future. Applying such products in UK urban areas is critical in the face of rapid population projections and timely in the wake of a series of extreme flooding events across the UK in recent winters and given the growing uncertainty on how the UK will set future water quality legislation in a post Brexit-WFD era.

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Conflicts of interest

We the authors confirm we have no conflict of interest in submitting this article for publication.

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